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Characterisation of the biofouling community on a floating wave energy device

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Abstract

Wave energy devices are novel structures in the marine environment and, as such, provide a unique habitat for biofouling organisms. In this study, destructive scrape samples and photoquadrats were used to characterise the temperate epibenthic community present on prototypes of the Pelamis wave energy converter. The biofouling observed was extensive and diverse with 115 taxa recorded including 4 non-native species. Vertical zonation was identified on the sides of the device, with an algae-dominated shallow subtidal area and a deeper area characterised by a high proportion of suspension-feeding invertebrates. Differences in species composition and biomass were also observed between devices, along the length of the device and between sampling dates. This research provides an insight into the variation of biofouling assemblages on a wave energy device as well as the potential technical and ecological implications associated with biofouling on marine renewable energy structures.

Keywords

non-native species, marine growth, marine renewable energy, epibiota composition, ROV surveys

Introduction

Global efforts to reduce greenhouse gas emissions and curtail the effects of climate change are driving demand for renewable and environmentally responsible energy generation (King 2004; IPCC 2007; United Nations 2015). Wave energy, in particular, represents a substantial renewable energy resource that is estimated to be in the same order of magnitude as the world consumption of electricity (Gunn & Stock-Williams 2012). The use of this global resource could therefore greatly contribute to the decarbonisation of the energy supply and future energy security.

The wave energy industry is currently in the pre-commercial phase with a number of prototype wave energy convertors being tested (Falcao 2010; IRENA 2014). Development of demonstration and commercial device arrays is likely to occur in the near future (Magagna & Uihlein 2015), and many sites are being planned for the Pentland Firth and Orkney waters, UK (Crown Estate 2011). This will represent substantial development in the marine environment, with the installation of artificial structures in the form of device arrays (hundreds of devices at the largest sites), support technologies (e.g. moorings, cabling, foundations and substations), and the expansion of local harbour infrastructure (Crown Estate 2011; Highlands and Islands Enterprise 2014). The submersed parts of any structures will be 'fouled' by marine epibenthic organisms (Dürr & Thomason 2010; Tiron et al. 2015), unless fouling prevention strategies are used; these strategies can include antifouling coatings (Almeida et al. 2007; Gittens et al. 2013), biofouling resistant materials (Powell & Michels 2000), seawater treatment (López-Galindo et al. 2010; Legg et al. 2015) and periodic cleaning (Woods et al. 2012; Roche et al. 2014).

The accumulation of biofouling organisms on wave energy devices could have technical implications. These are well documented in other marine industries and issues likely to be relevant for the wave energy industry are numerous (Table 1). A unique consideration for the wave energy industry is that biofouling may also limit energy extraction by both reducing the efficiency of the power take-off system and by increasing device maintenance time (Langhamer et al. 2009; Tiron et al. 2014; Tiron et al. 2015).

There are also a number of ecological implications associated with the accumulation of biofouling on marine energy devices. If biofouling is not controlled, devices and support structures will function as secondary artificial reefs (Wilhelmsson & Malm 2008;

Langhamer et al. 2009; Krone et al. 2013). This could have a positive impact on the local environment through increased nutrient availability and enrichment of the surrounding macrobenthic community (Langhamer 2010; Coates et al. 2014), and could result in the recruitment of higher trophic level species such as fish and decapods due to the increased food supply and the provision of shelter by the structures (Svane & Petersen 2001; Langhamer & Wilhelmsson 2009; Reubens et al. 2014). However, there may also be negative impacts indirectly associated with biofouling communities such as detrimental local trophic changes (Davis et al. 1982; Ambrose and Anderson 1990), loss of soft sediment biotypes surrounding devices (Bomkamp et al. 2004; Goddard & Love 2010), and the creation of ecological traps (Hallier & Gaertner 2008). A major ecological concern is the potential for wave energy structures to facilitate the introduction, establishment, and spread of fouling non-native species (Mineur et al. 2012; Adams et al. 2014; Nall et al. 2015).

There is a paucity of information on the type of biofouling assemblages likely to develop on a wave energy device, and therefore the associated technical and ecological consequences are difficult to predict. While there have been many studies characterising biofouling assemblages on coastal/offshore artificial structures, such as wind turbine foundations and oil and gas platforms (Forteath et al. 1982; Kerckhof et al. 2011; Vanagt et al. 2013; van der Stap et al. 2016), these communities will not necessarily be analogous to those expected to develop on wave energy devices, and may be of limited comparative value.

Biofouling assemblages on wave energy devices are likely to differ from those on other marine structures because in many cases they will experience different abiotic environments. For instance, many wave energy devices are shallow floating structures (IRENA 2014); biofouling assemblages on floating structures are notably different from those on fixed structures (Connell 2000; Holloway & Connell 2002) and tend to contain more non-native species (Glasby et al. 2007; Dafforn et al. 2009). Assemblages on floating structures are thought to be distinct from other marine habitats because they are consistently exposed to the same shallow subtidal depth with little air exposure (apart from in the splash zone above the waterline and the 'swash' zone *sensu* Holloway and Connell 2002). They are also isolated from the sea floor (potentially reducing sedimentation and predation), exposed to differences in light intensity (high intensity and low intensity where shaded by the

structure) and experience surface hydrodynamic turbulence (Holloway & Keough 2002; Perkol-Finkel et al. 2006; Perkol-Finkel et al. 2008).

Compared to other floating structures, floating wave energy devices may provide unique habitat because they will be placed close to shore in highly energetic wave environments, and are often larger and more structurally heterogeneous than other floating structures such as navigation buoys (having varying surface orientations, complex surface topographies, and moving components). These factors are known to increase species diversity and biomass of epibenthic communities and thus could contribute to a unique and diverse biofouling community (Svane & Petersen 2001; Tokeshi & Arakaki 2011; Norderhaug et al. 2012; van der Stap et al. 2016).

Current benthic ecology studies on wave energy devices have been focused on changes to the natural benthic communities surrounding renewable energy devices (Langhamer 2010; Broadhurst & Orme 2014; Coates et al. 2014) or on the artificial reef effects of device foundations (Langhamer et al. 2009; Langhamer & Wilhelmsson 2009). There have also been studies assessing the biofouling communities that develop on navigation buoys which are thought to be analogous to smaller point absorbing wave energy devices (Langhamer et al. 2009; Macleod et al. 2016). This study represents the first time a biofouling community has been described from a wave energy device and it provides a basis for assessing technical and ecological impact scenarios related to biofouling in the wave energy industry.

Methods

Pelamis wave energy converter

The Pelamis P2 wave energy converter is a 180m long and 4m wide semi-submerged wave attenuator, which takes its name from the sea snake, *Pelamis platurus*. These devices weigh ~1300 tonnes and are composed of 5 cylindrical sections (referred to as 'cans') which are connected at intersections by hinged joints. Wave motion drives movement in the hinged joints and this is harnessed to generate electricity (Yemm et al. 2012).

Two P2 devices were available for biofouling surveys. Both devices were assembled in Leith Docks, Edinburgh and then towed ~500km to Orkney to undergo sea trials. Components of P2-001 were first 'launched' at Leith Docks in January 2010, with delivery to Orkney in August 2010. P2-002 was launched in April 2011 and delivered for testing in November 2011. Sea trials were conducted at the European Marine Energy Centre (EMEC) Billia Croo wave test site (Figure 1), off the west coast of mainland Orkney, Scotland (58.9719°N 3.3684°W). This area experiences typical wave heights of 2m and in extreme conditions wave heights can be >10m (Lawrence et al. 2009). When not deployed at the wave test site, Pelamis devices were berthed at Lyness harbour (58.8350°N 3.1907°W) on the Orkney island of Hoy (Figure 1). The deployment schedules were irregular and differed between the two devices (Figure 2). All surveys were conducted when the devices were berthed at Lyness, in April 2014 and June 2014.

Different sections of the Pelamis device potentially provided different habitats for biofouling species. For this reason the biofouling assemblages of a number of sections of the devices were surveyed: the sides of the cans and intersections between cans at the waterline, deeper areas of the intersections, and the undersides of cans.

Destructive sampling

Biofouling scrape samples from the P2-002 device were collected in April 2014. Six scrapes were taken from the sides of the cans ('outer surface'), and the can intersections respectively (Figure 3). Scrape samples were approximately 15x15cm and were taken at haphazard locations on the cans from just below the waterline (0-0.25m depth) using a purpose-built scraper (essentially a kick-net with a metal lip at the base). Sampling areas were accessed using a small motorised boat.

Deeper sampling (~0.5m-2m depth) was undertaken at 2 intersections on the device. This was possible because a watertight compartment (referred to as the 'habitat') had been installed at these intersections for maintenance purposes, permitting access to normally submerged parts of the intersections. Using a paint scraper and a collection tray, several 15x15cm samples were taken from intersection 2 (n=3). A rapid assessment survey (e.g. Bishop et al. 2015; Collin et al. 2015; Nall et al. 2015) of intersection 3 was carried out to search specifically for fouling non-native species known to be present in Scotland (Nall et al. 2015).

Samples were fixed in phosphate-buffered formalin (4% formaldehyde in distilled water) and after 2 weeks were transferred to 70% ethanol for preservation and storage. Organisms were identified to the highest possible taxonomic resolution and the wet biomass (rounded to the nearest 0.01 g m^{-2}) of each taxon was measured. Species considered non-native to the UK were noted based on checklists of non-native species present in British waters (Eno et al. 1997; Minchin et al. 2013; Nall et al. 2015).

Bulk biomass sampling

Further 15x15cm scrape sampling was carried out at the waterline (0-0.25m depth) to investigate differences in biofouling biomass between devices; scrape samples were taken from the outer surface of cans on the P2-001 and P2-002 devices in April 2014. The effect of sampling location (outer surface and intersection areas), and the immediate effect of deployment at the wave test-site on the biomass of biofouling was also assessed on the P2-002 device, using scrape samples taken in April 2014 and in June 2014. The total wet biomass (g m^{-2}) of each scrape was measured.

ROV photoquadrat sampling

Biofouling on the underside of both P2-001 and P2-002 devices (Figure 3) was surveyed using an Outland 1000 remotely operated vehicle (ROV). A Canon Powershot S95 camera in an Ikelite housing was attached to the front of the ROV in an upwards-facing position, with an Inon S-2000 strobe for illumination. A custom script (Ultra-intervalometer/CHDK http://chdk.wikia.com/wiki/CHDK) was used to set the camera to record one image every 10 seconds. Two parallel Z-Bolt 5mW underwater laser pointers were calibrated to indicate two points 15cm apart, within the camera field of view. The ROV was piloted slowly along the underside of the Pelamis devices, allowing the camera to collect images of the underside

of the devices. The length of the ROV tether did not allow the entire length of both devices to be surveyed. Sampling was conducted in April and June 2014 (Figure 2); the June sampling period occurred immediately after the P2-002 had returned to Lyness after a month-long deployment at the EMEC wave test-site, in what was described as a small wave climate (Pelamis Wave Power Ltd. pers. com.).

Images were graded for quality according to a series of criteria (see Table S1), and only those of high quality, graded 3 or 4, were used for quantitative analysis. In April 2014, suitable images were collected from P2-001 (Cans 1 and 2) and P2-002 (Cans 1-3); while in June 2014 only the P2-002 (Cans 1-4) was available for survey. Six images were analysed from each can for each sampling date, using PhotoQuad (Trygonis & Sini 2012). Images were calibrated using the known distance between the laser scaling points (15cm), and a single 15cm x 15cm area on each image was defined as a 'photoquadrat'. Percent cover of fouling taxa within each photoquadrat was measured using a random point method. Random points (64 per photoquadrat) were generated using the 'Stratified Random' command (one point is placed in each of 64 equal sized squares within the defined photoquadrat), and the biofouling under each point was assigned to one of 27 biofouling categories (Table 2). These data were used to estimate percent cover for each biofouling category.

In addition to the images collected during the ROV survey, a range of 'opportunistic' digital still images were available. These included images collected during sampling visits and some images provided by Pelamis Wave Power Ltd (which had been collected during routine maintenance). These images (together with all ROV images) were examined and used to compile a species list for the two devices.

Data analysis

Multivariate analyses of species assemblage data from the scrape and ROV quadrat samples were performed using PRIMER v6 with PERMANOVA (Clarke & Gorley 2006; Anderson et al. 2008). A fourth-root transformation was applied to the species biomass and percent cover data to downweight the contribution of quantitatively dominant species and Bray-Curtis similarity matrices were constructed (Bray & Curtis 1957). Ranked similarity values between samples were plotted using non-metric multi-dimensional scaling (MDS) ordinations. PERMANOVA tests were used to test for significant differences in biofouling assemblages between the outer surface and intersections at ~0-0.25m and between the two

depth categories within the intersections. For the photoquadrat data, fouling composition in April 2014 was compared between the two devices using a nested PERMANOVA test with 'Can' nested within 'Device'. Similarly, the fouling composition was compared between the April and June 2014 survey dates for P2-002, using another nested PERMANOVA with 'Can' nested within 'Sampling date'. SIMPER analyses were used to explore which fouling categories contributed most to any dissimilarities that were detected between sampling locations for both scape and photoquadrat data.

Mann-Whitney U tests were used to assess the effect of sampling location on the biomass of non-native species, the species richness (total number of species present per scrape), and the abundance of certain taxonomic groups from scrape samples. A one-way ANOVA was performed to investigate differences in the total biomass measures across the two devices. Data were $\log_{10}$ transformed to fit the assumption of normality and due to heteroscedasticity the test was adjusted with the Welch statistic. A two-factor GLM was used to investigate differences in the total biomass between sampling locations and before and after deployment at the energy extraction site. Prior to the GLM, biomass data were square-root transformed to achieve normality. Univariate analyses were performed using SPSS Version 22.

Results

All areas surveyed on Pelamis were extensively biofouled with very little bare surface visible (Figure S1 in Supporting material). In total, 115 taxa were recorded (Table S2 in Supporting material). Across the survey areas, the greatest diversity was found from the scrape samples at the waterline with 66 taxa. In the other survey areas, 52 and 45 taxa were observed from the deeper scrapes samples and the ROV images, respectively.

Destructive sampling

Biofouling at the waterline

On the outer surface (O) algae accounted for 76% of the total mean biomass whilst in the intersections (I) it accounted for 50% (Figure 4); this difference was significant (Mann-Whitney $U_{(12)}$ = 0.000, p = 0.002; mean biomass g m^{-2}±se: O = 1840.1±271.2, I = 896.5±142.6). Green and brown algal species *Acrosiphonia arcta, Ulva* sp., *Alaria esculenta* and *Chorda filum* were the main taxa contributing to this difference although it was noted that a greater abundance of red algae was present in the intersections, particularly *Polysiphionia* sp. (Table S2). Arthropoda (mostly the barnacle *Balanus crenatus*: O = 13.4%, I = 29.3%) and Tunicata (mostly *Diplosoma listerianum*: O = 6.9%, I = 14.7%) accounted for most of the invertebrate biomass in both areas. Cnidaria (in particular *Tubularia* sp.: I = 3.5%) also contributed to a sizable proportion of the mean biomass in the intersection sampling area.

Despite differences in algal biomass, there was no significant difference between the composition of biofouling assemblages on the outer surface and intersections (PERMANOVA: $F_{(1,11)}$ = 1.822, p = 0.065). There was also no significant difference in species richness between these areas (Mann-Whitney $U_{(12)}$ = 15.000, p = 0.699; Total number of species: O = 57, I = 45).

In both sampling areas, invertebrates represented a large proportion of the total species richness (O = 55%, I = 60%) (Figure 4). Arthropoda contributed more to the species richness than any other invertebrate phyla; this included amphipods (e.g. *Gammarellus angulosus*) and isopods (e.g. *Idotea pelagica*), barnacle species (principally *B. crenatus*) and the pycnogonid, *Phoxichilidium femoratum*. Mollusca, Annelida and Cnidaria also contributed substantially to species richness in both areas.

Two non-native species were present; *Dasysiphonia japonica* (=*Heterosiphonia japonica*) and *Schizoporella japonica*. Neither species was abundant in either surveyed area. *Dasysiphonia japonica* represented 1.6% of the total mean biomass on the outer surface and 1.0% in the intersections (g m^{-2}±s.e.: O = 37.19±29.49, I = 17.93±12.41), whilst *S. japonica* was only present in a very small quantity in the outer surface sample area (representing 0.01% of the mean biomass; g m^{-2}±s.e.: 0.15±0.15). There was no significant difference in their biomass between the outer surface and intersections (Mann-Whitney, *D. japonica*: $U_{(12)} = 17.00$, $p = 0.937$; *S. japonica*: $U_{(12)} = 15.00$, $p = 0.699$).

Biofouling at ~0.5-2m depth

In the deeper scrape samples taken from intersection 2 of the P2-002 device, the most consistently abundant fouling types (g m^{-2}±se) included *Diplosoma listerianum* (300.96±52.86), *Ascidiella aspersa* (220.44±87.99), *B. crenatus* (195.11±148.07), and empty barnacle/ serpulid shells (853.78±71.50). A large proportion of the mean biomass was also represented by *Mytilus edulis*, *Asterias rubens*, and *Metridium dianthus*, but these species were not consistently present in the samples. These 7 taxa represented 91% of the mean biomass and heavily influenced the contribution of each phyla to the mean biomass (Figure 5). However, many additional invertebrate species were recorded. Annelida, Bryozoa, Arthropoda, and Cnidaria accounted for 22%, 19%, 17%, and 13% of the species richness (Figure 5). The deeper subtidal invertebrate community included several sessile filter feeders: e.g. the polychaetes *Sabella pavonina* and *Spirobranchus triqueter*; the bryozoans *Scrupocellaria scruposa* and *Callopora dumerilii*; the molluscs *Hiatella arctica* and *Anomia ephippium*; and the barnacles *B. crenatus* and *B. balanus*. This part of the intersection also supported mobile species such as the predatory polychaete *Nereis pelagica*, amphipods, and juvenile crab species. Other notable taxa included the hydroids *Eudendrium* sp. and *Tubularia* sp., and the soft coral *Alcyonium digitatum*. No algae were present in these samples.

The difference in biofouling assemblages between the two depth categories was significant (PERMANOVA: $F_{(1,8)} = 6.707$, $p = 0.004$), and a distinct separation was visible in the nMDs plot (Figure S2). Dissimilarity was driven mainly by the absence of algae from the deeper sections and a greater abundance of empty barnacle/ serpulid shells, *Ascidiella aspersa*, and *M. edulis* in the deeper sections sampled (SIMPER; Table 3).

Non-native species (g m^{-2}±se) found in the deeper sections of the intersections included *Corella eumyota* (0.59±0.59), *Caprella mutica* (2.96±1.67), and *Schizoporella japonica*. The cryptogenic species *Bugulina fulva* (previously known as *Bugula fulva*) was also found. The latter two species were found during the rapid survey of intersection 3 so no abundance measure was recorded. In the quantifiable samples of intersection 2, non-native species accounted for 4.1% of the species richness and 0.1% of the mean biomass.

Biomass of biofouling at waterline

There was a significantly greater (Welch ANOVA: $F_{(1,16.728)} = 27.881$, $p < 0.001$) biomass of biofouling at the waterline of the outer surfaces of the P2-002 device (Mean biomass g m^{-2} ±se: 2207.51 ±259.95) compared to the P2-001 device (799.56 ±151.01) (Figure 6).

Sampling area (outer surface vs. intersection) significantly explained differences in biomass between treatments (GLM: $F_{(1,36)} = 5.220$, $p = 0.028$; Table S3), but deployment and the interaction of factors did not. Scrape samples from the outer surface had a greater biomass than those from the intersections, both pre- and post-deployment at the energy extraction site (Figure 6).

Photoquadrat data

The undersides of all surveyed cans on both Pelamis devices were extensively fouled (Figure 7); the average percentage cover across all photoquadrats was 93.6% (± 6.36%). The most common fouling organisms were anemones (particularly *Metridium dianthus*), soft corals (*Alcyonium digitatum*), ascidians (particularly *Diplosoma listerianum*), mussels (*M. edulis*), and barnacles (mainly *B. crenatus*). Substantial areas were also fouled by 'turf' species, which were difficult to consistently identify with high taxonomic resolution, but mostly consisted of hydroids and bryozoans. In addition, 3 non-native species (*Corella eumyota*, *Caprella mutica*, and *Schizoporella japonica*) were recorded on the P2-001 device from 'opportunistic' images not used in the photoquadrat analyses.

When surveyed in April 2014, the fouling assemblage differed significantly between the two Pelamis devices, but not among cans on each device (Table 4; Figure 8). Since the 'Can' factor was non-significant, all levels of this factor were pooled for the SIMPER analysis. P2-001 had greater abundance of *M. dianthus,* mussels, and soft corals, while P2-

002 had greater abundance of didemnid ascidians (mostly *Diplosoma listerianum*), 'turf' species, and *Urticina* spp. anemones (Table 5; Figure 7; Figure S3).

Fouling composition on P2-002 differed significantly between the April and June 2014 sampling dates and among 'Cans' (Table 6). Pairwise testing appeared to show that while there was no significant variation among cans in April, there was in June (Table 6). SIMPER analyses suggested that the dissimilarities between April and June resulted from greater percent cover of didemnid ascidians in April, and somewhat greater abundances of anemones, soft corals, and hard fouling types such as barnacles and tubeworms in June (Table 7; Figure 7; Figure S3). In June, it appeared that Can 3 differed from the others sampled, having reduced cover of hard fouling types (barnacles and tubeworms) and ascidians (particularly didemnidae), less unfouled surface, and greater cover of *Urticina* spp. (Figure 7).

Discussion

Characteristics of the biofouling community on Pelamis

A total of 115 taxa were recorded on the sampled Pelamis devices, and there was a high degree of variation between samples, both between and within areas surveyed. In the scrape sampling survey, two different biotopes were observed from the P2-002 device: the shallow subtidal area just below the waterline (0-0.25m water depth) and the deeper subtidal area in the intersection (0.5-2m).

The biofouling of the shallow subtidal area was dominated by algae *Alaria esculenta*, *Acrosiphonia arcta*, *Ulva* sp., and *Polysiphonia* sp., as well as understory invertebrates *B. crenatus* and *Diplosoma listerianum*. This habitat could not be confidently attributed to a biotope in the JNCC Marine Habitat Classification (Connor et al. 2004; Irving & Wood 2007). However, it did share some physical and biological attributes with the high energy infralittoral rock *Alaria esculenta* dominated biotope, IR.HIR.KFaR.Ala. The algae assemblage was also similar to those found on the submerged upper regions of offshore oil and gas structures in the North Sea and on navigation buoys in the Moray Firth (Terry & Picken 1986). In the shallow subtidal area, there was no significant difference between the species assemblages of the outer surfaces and intersections of the device. However, total biomass was greater on the outer surfaces, and there was a greater abundance of algal species belonging to the Chlorophyta and Ochrophyta. Shading within the device intersections is likely to be the explanation for reduced algal abundances (Glasby 1999; Irving & Connell 2002) compared to the outer surfaces, where light levels are higher.

The biofouling in the deeper areas of intersections contained no algae and mostly consisted of suspension feeders and vagile scavengers. This deeper assemblage shared similar species (e.g. *M. edulis*, *Metridium dianthus, B. crenatus*, *Ascidiella aspersa*, *Anomia ephippium*, and *Hiatella arctica*) to those recorded in the ROV photoquadrat survey of the undersides of Pelamis, and also to those from previous surveys of biofouling on the lower sections of navigation buoys in Orkney and off the Swedish coast (Langhamer et al. 2009; Macleod et al. 2016). The transition from the algae-dominated shallow areas to deeper invertebrate-dominated communities displays typical vertical zonation seen on many other offshore and coastal structures (Terry & Picken 1986; Yan et al. 2009; Kerckhof et al. 2010).

Many species recorded in this study were typical of high energy environments. *Metridium dianthus*, *Alcyonium digitatum* and *M. edulis*, observed in high abundance on the undersides of Pelamis, are known to thrive in areas of strong water movement (Bayne 1976; Hartnoll 1977; Sebens & Koehl 1984; Butman et al. 1994) and are dominant species in JNCC Marine Habitat biotope of fouling fauna on exposed steel wrecks: CR.FCR.FouFa.AdigMsen (Connor et al. 2004; Irving & Wood 2007). Epibenthic communities with high abundances of *Alaria esculenta, B. crenatus*, *Spirobranchus triqueter,* and *Tubularia* sp., are also known to occur at high energy sites (de Kluijver 1993; Connor et al. 2004; Irving & Wood 2007). The amphipod *Gammarellus angulosus,* found in abundance in the shallow subtidal area of the device, naturally occurs in algae on highly exposed rocky shores (Steele & Steele 1972), and colonises drifting seaweed along with another amphipod species found on the device, *Dexamine thea* (Ingólfsson 1995; Ingólfsson 2000). Congeners of *Jassa herdmani* and *Monocorophium* species are highly abundant on offshore structures (Kerckhof et al. 2009; Vanagt et al. 2013), and *J. herdmani* has been observed to show a preference for high flow environments (Macleod 2013).

Differences in biofouling assemblage between devices and sampling dates

The ROV photoquadrat survey in April 2014 indicated there were differences in the biofouling assemblages between the two Pelamis devices. The underside of P2-001 had a much greater coverage of anemones and mussels, while the underside of P2-002 was dominated by ascidians (especially *Diplosoma listerianum*), and low level animal fouling 'turf' (appearing to be made up of mainly hydroids and foliose bryozoans, along with some other foliose and encrusting soft foulers). There was also a significant difference between the total biomass of biofouling at the waterline between the P2-001 and P2-002 devices in April 2014, further confirming differences in the biofouling communities between the devices. During their operational life both devices have been located in the same sites and neither of them had ever been cleaned. It can therefore be conjectured that differences in the biofouling communities between devices are due to differences in the age of the devices and because each device had had different deployment and storage schedules (Figure 2).

Alternate communities can be produced through succession due to variation in the order of initial colonising species, specific interactions between later colonising species and resident adults and as a result of differences in environmental disturbance (Sutherland 1974;

Connell & Slatyer 1977; Osman 1977). Sections of the P2-001 and P2-002 device had been in the water since January-March 2010 and April 2011 respectively. Annual and seasonal variation in the assemblages of the initial colonisers could therefore have contributed to the observed differences in species assemblage between devices although there is a large body of evidence suggesting marine benthic communities can converge to a single stable point of late colonising dominant species regardless of the order to colonising species (eg Scheer 1945; Antoniadou et al. 2011; Pacheco et al. 2011). Due to their difference in age it is also possible that the communities on the devices were at different successional stages. The substantial presence of slow growing and long lived secondary colonisers such as *Metridium dianthus* and *Alcyonium digitatum* (particularly on the older P2-001 device) indicated that the biofouling community might have been approaching the later stages of succession. Biofouling communities can reach maturity in 2-5 years after a structure has been installed (BMTCordah 2013; Macleod 2013). However, they can also remain dynamic for up to 20 years (Butler & Connolly 1999; BMTCordah 2013), so it is possible that the assemblages on these devices may continue to change.

The biofouling assemblages on operational wave energy devices are also likely to be affected by the changing environmental conditions experienced when devices are moved between offshore energy extraction sites and sheltered storage locations. This is particularly pertinent for prototype devices (such as Pelamis) which are typically expected to undergo many deployments and retrievals in their lifetime. The history of these environment disturbances is relevant to the assemblage of biofouling at the time of surveys both as a direct consequence of a recent perturbation to species in the biofouling community (e.g. physical removal) and how it shapes succession of community in the long term (Sutherland 1974).

Both devices underwent different deployment schedules (Figure 2) with one device (P2-001) that was near inactive for all of 2013 and then had one deployment before it was sampled in April. The other (P2-002) was much more active in 2013 having several deployments right up to October, before being inactive over winter. It was then deployed at the test site for a period in between the two sampling dates. Fouling species that have a short-lived and seasonal presence in biofouling communities (e.g. some amphipods and hydroids, McDougall 1943) may have settled or regrown whilst the devices were moored in Lyness harbour in the time prior to sampling. Sheltered conditions maybe more favourable for these

species and it is possible that the hydrodynamic forces experienced at the wave energy extraction site caused the physical removal or die-back of certain species that developed whilst in the sheltered harbour location. The low proportion of *Diplosoma listerianum* observed from on P2-001 in April 2014 could have been a result of these species being removed whilst the device was deployed in March 2014 (a week prior to the survey). A previous study by Coutts et al. (2010) has shown that *Diplosoma listerianum* present in the hull fouling community of vessels suffer considerable losses in coverage after fast vessel movement. The inability of this species to cope with high hydrodynamic forces is further indicated from its observed reduction in its coverage on the P2-002 device post-deployment. After the deployment there also appeared to be some minor differentiation among cans of the P2-002 device which had not been observed on either device in the April 2014 samples. The deployment of the device at the wave test site at Billia Croo may have driven these changes in the biofouling assemblages, particularly since hydrodynamic conditions may vary along the length of such a device (Thiam & Pierce 2013). However, it is also likely that there were seasonal influences on biofouling composition (McDougall 1943; Osman 1977; Brown 2005; Reiss & Kröncke 2005), since two months passed between sampling visits.

How device deployment history and season has impacted the composition of biofouling assemblages on the Pelamis devices is difficult to determine from this 'snapshot' study of biofouling. Future studies should sample over a longer period of time, monitoring how deployments impact the community composition. Experimental settlement panels at both storage location and energy extraction site may also help to explore how deployments influence succession of the fouling community.

Other habitats on Pelamis

Wave energy devices such as Pelamis are structurally complex, with a number of potential habitats for fouling organisms, including some that were not surveyed in this study (Figure 9). Examples include the wave-wash/splash zone, internal heat exchanger compartments (which are likely to be treated with biocide), and numerous crevices throughout the device, particularly at the joints. These niche areas are likely to provide differing environmental conditions to the areas surveyed and therefore could host different biofouling assemblages. For instance, the wave-wash/splash zone above the waterline will be exposed to long periods of desiccation and is likely to provide an ideal habitat for upper-littoral species (Terry &

Picken 1986; Arenas et al. 2006). The non-native marine splash midge *Telmatogeton japonicus* (Brodin & Andersson 2009) could also colonise this area, although it is currently not known in Scotland (Nall et al. 2015). The heat exchanger compartments provide a shaded area, sheltered from wave action and are likely to provide a similar environment for biofouling organisms as ship sea-chests (Coutts & Dodgshun 2007). The areas surrounding heat exchangers are likely to be treated with copper ions, therefore fouling organisms settling here will need to be tolerant of copper dosing (Reed & Moffat 1983; Piola & Johnston 2006). Fully comprehensive inventories of biofouling organisms on wave energy devices would need to include these areas.

Occurrence of non-native species

Four non-native species (*Caprella mutica*, *Corella eumyota*, *Dasysiphonia japonica*, and *Schizoporella japonica*) and 1 cryptogenic species (*Bugulina fulva*) were found on the Pelamis devices. All non-native species found on the devices were already known to be present in Orkney and all but *Schizoporella japonica* had previously been recorded from Lyness Harbour (Nall et al. 2015). It is likely that *Schizoporella japonica* was introduced to the Pelamis devices and Lyness harbour through secondary introduction via vessel hull-fouling, rather than natural dispersal, since it has only a short lecithotrophic larval period (Treibergs 2012). Over time, other non-native species may be introduced onto the device via the same means. However, not all non-native species may be capable of colonising renewable energy devices. Despite the non-native alga *Codium fragile fragile* being present on harbour structures in Lyness Harbour (Nall et al. 2015) it was not found on the Pelamis device. *Codium* is known to grow on floating structures in sheltered harbours (Chavanich et al. 2006; Nall et al. 2015); its absence from Pelamis could be a result of competition from other canopy forming algae (Scheibling & Gagnon 2006), or due to its apparent lower tolerance for wave exposure (Trowbridge 1998; Bulleri et al. 2006; D'Amours & Scheibling 2007).

Although present on the Pelamis device, non-native species appear to play a minor role in the composition of biofouling. Non-native species accounted for <5% of the species richness and contributed very little to the total biomass in all the areas surveyed. *Dasysiphonia japonica* was the most abundant non-native species contributing between to 1.6% and 1.0% of the total biomass in the outer surface and intersection areas. A previous study by Macleod (2013) investigating the biofouling assemblages on navigation buoys in

Orkney waters, also found that non-native species represented a small proportion of the species richness (1.6%). In Macleod (2013), *Caprella mutica* was however found to be present in high densities and it was a key species responsible for differences in navigation buoy assemblages between Orkney and other locations in the UK. The low abundance of *Caprella mutica* in this survey could be a result of the time of year that sampling was conducted. The phenology of *C. mutica* in Scotland shows seasonal changes in abundance, with a peak abundance in late summer and low abundance or absence during the time of these surveys (Ashton 2006).

In a study of marine growth on wind turbine pylons in the southern North Sea, non-native species made up a much higher proportion of the species richness (33.3%) (Kerckhof et al. 2011). However, despite the low abundance and diversity of non-native species on Pelamis, their presence confirms the potential for marine renewable energy devices to provide habitat for these species. Based on studies showing that vessel movement has a limited impact on the survivability of hull fouling species (Coutts et al. 2010; Kauano et al. 2016) it is likely that these devices could also act as vectors for the transfer non-native species when they are wet-towed. Deployment of devices contaminated with non-native species at energy extraction sites could facilitate the transfer and subsequent establishment of non-native species into the local natural environment and to other structures and coastlines previously disconnected by biogeographical barriers via the 'stepping stone effect' (Adams et al. 2014; Airoldi et al. 2015). In a similar way to the oil and gas industry, long distance tows of floating devices for the initial delivery from the fabrication site or for decommissioning purposes may provide a particularly high risk pathway for non-native species introduction if the biofouling community is contaminated with non-native species (Wanless et al. 2009).

In the case of Pelamis, the cans of both devices were moored at Leith docks in Edinburgh for periods of 5-7 months prior to being wet-towed to Orkney for delivery. This was ample time for biofouling species to have colonised the structures whilst in Edinburgh, as macrobiofouling organisms can settle and become established within weeks of a structure being submerged (Wahl 1989; Floerl & Inglis 2010). It is unknown whether this resulted in the secondary spread of non-native species to Orkney, as there is no information on the fouling species present on Pelamis prior to delivery, and there is currently no evidence of new species arriving in Orkney on wet-towed wave energy devices.

Other implications of biofouling in the wave energy industry

The formation of biofouling assemblages on wave energy devices can have other ecological implications, which can be considered beneficial or detrimental. A diverse and biomass rich biofouling community was present on Pelamis, and the formation of hard-substratum assemblages on secondary artificial reefs (such as marine renewable energy devices) has been shown to increase biomass and biodiversity in the locality (Wilhelmsson & Malm 2008; Langhamer et al. 2009; Krone et al. 2013). This can have a wider impact on the local environment through increased nutrient availability in the form of deposition of organic matter to the surrounding benthic environment (McKindsey et al. 2011; Coates et al. 2014). This has been associated with further increased local productivity, with increased density and diversity of benthic macrofauna in the soft sediments adjacent to artificial structures (Barros et al. 2001; Langhamer 2010; Coates et al. 2014).

The enhanced food supply and increased feeding efficiency provided by biofouling assemblages and enriched macrobenthos further contributes to the aggregation and recruitment of higher trophic level species such as fish and decapods (Svane & Petersen 2001; Langhamer & Wilhelmsson 2009; Reubens et al. 2014). This in turn may attract piscivorous predators such as marine mammals (Todd et al. 2009; Todd et al. 2016). It should be noted that the shelter against predation and currents provided by the structures and the biofouling itself will also contribute to the aggregation and recruitment of higher trophic level species (Pickering & Whitmarsh 1997; Langhamer & Wilhelmsson 2009). The combination of food availability and shelter create an ideal habitat for crab larvae and juveniles (Moksnes 2002) and the presence of a number of juvenile crabs (*Cancer pagurus*, *Hyas* sp., *Necora puber*, and another unidentified species) on Pelamis indicates the potential for renewable energy structures to serve as habitat for commercially important species. It is possible that these artificial reef effects combined with the exclusion of fishing activities from the vicinity of energy farms (MCA 2008) will in time result in an increase in the abundance of commercially exploited species (such as *Gadus morhua*, *Cancer pagurus* and *Homarus gammarus*) and in turn provide conservation and economic benefits (Jensen et al. 1994; Lokkeborg 2002; Gill 2005; Hooper & Austen 2014).

Although artificial reef effects can largely be viewed as positive, alterations to local fauna can cause detrimental trophic changes and certain biotopes could be lost, particularly in

soft sediment environments. Increased predatory pressure to surrounding benthic macrofauna could reduce the abundance of some prey species (Davis et al. 1982; Ambrose & Anderson 1990). These impacts are complex and largely dependent on the particular habitat and faunal community present before the development. However, even if devices are deployed in a hard-substratum area, alterations could still occur due to increased habitat space and complexity (Wilhelmsson & Malm 2008; Schläppy et al. 2014), and also because biofouling assemblages forming on the artificial structures can differ from those on nearby natural substrata (Connell 2001; Smith & Rule 2002).

Biofouling will also have technical implications with respect to operation, maintenance and life expectancy of wave energy devices (Table 1). Floating devices are likely to have thicker biofouling than other marine structures due to the presence of larger organisms, such as kelp and mussels, at shallow depths (Forteath et al. 1982; BMTCordah 2013). Other considerations include increased structural weight and hydrodynamic loading which will reduce buoyancy and increase stress and fatigue. This may have a greater impact than reported for offshore oil platforms (Jusoh and Wolfram 1996; Yan and Yan 2003) and offshore wind turbines (Shi et al. 2012) due to the smaller size and structural weight of wave energy devices.

In this study, biomass of biofouling in the shallow subtidal area (0-0.25m depth), amounted to approximately 2.5kg m^{-2} (based on the mean of pooled samples from outer surface in April and June 2014). This represents a total estimate of biomass in the shallow subtidal area of 22.8tn, which is 0.7% of the total weight of the 3000tn device. This is only a small proportion of the device weight and therefore it is unlikely the addition of biofouling biomass will have any technical implications in terms of addition of structural weight. The true weight of the biofouling in water will also be less due to a large proportion of the biofouling being non-calcareous ('soft' fouling organisms) which have a similar density to water (Macleod et al. 2016). The increased diameter and surface roughness associated with biofouling will increase the hydrodynamic loading and will have technical implications for the mooring design and the functionality of the Pelamis device (Jusoh & Wolfram 1996). In the aquaculture industry, biofouling has been shown to reduce the life span of mooring lines due to increased hydrodynamic forces and mechanical strain (Braithwaite & McEvoy 2005).

Representatives of Pelamis Wave Power indicated that they were not aware of any performance issues related to biofouling but that accumulation in certain areas did necessitate some cleaning during operation and maintenance of the P2 devices (pers. com. Beth Dickens - formerly with Pelamis Wave Power). This included removal of biofouling from subsea cable connectors prior to device deployment and removal of fouling at the edge of the intersections to achieve a watertight seal with the 'habitat' device.

Conclusions

This study provides an insight into the extensive epibenthic communities that can develop on floating wave energy devices. In particular, it indicates the variety of communities expected to form across an individual device and between devices, and it demonstrates the changes that can occur to species composition as a result of season or the movement of the device between sheltered and exposed sites. A fully operational, commercial scale wave energy array will consist of a number of devices, each with differing ages and varied deployment and maintenance histories. Consequently, while there will be similarities between the assemblages on individual devices, there will also be significant variation as observed in this study. Arrays of other types of devices in other locations will inevitably show some differences from the assemblages recorded here, given the variation in device design and the differences in environmental conditions and propagule supply. However, there will be similarities, and the biofouling community reported in this study is likely to share some similarities with those that will form on other wave devices and analogous floating structures such as tidal stream and wind energy devices. This study provides a basis for hypothesising impact scenarios of these devices and similar structures, including the establishment of non-native species, technical implications and artificial reef effects. The presence of non-native species on Pelamis demonstrates the potential for marine renewable devices to aid the spread of non-native species, particularly if devices are wet-towed to various locations during delivery, maintenance or decommissioning.

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Figures

Figure 1 Locations for the Billia Croo wave test site and Lyness harbour renewable energy storage and maintenance facility in the Orkney Islands, Scotland. The aerial image of Lyness harbour shows the P2-001 and P2-002 Pelamis wave energy converters berthed alongside the wharf. Image source for Lyness aerial image: http://www.bing.com/maps/

Figure 2 Timeline for the deployment schedule of the Pelamis devices at the Billia Croo wave test site (grey bars indicate periods at the test site). The black lines in 2014 mark the primary sampling dates of the biofouling surveys, 'L' marks the initial launch of the devices at Leith Docks, Edinburgh and 'D' marks the towed delivery of devices to Lyness harbour, Orkney.

Figure 3 Biofouling sampling plan for the Pelamis wave energy converter. Replicates from the outer surface are displayed in black and replicates from the intersections are displayed in grey (n=12). Some cans were sampled twice to maintain a balanced experimental design. Deeper sampling (~0.5m-2m depth) was also carried out at intersection 2 and 3.

<<Editor: ''underside'' should read ''Underside'', ''side of cans'' = ''Side of cans'' and ''intersections'' = ''Intersections''>>

Figure 4 Proportion of wet biomass (g m^{-2}) and species richness (N) of each phylum in the outer surface and intersection sample areas of P2-002 device at ~0-0.25m water depth. Wet biomass percentages were calculated from the mean biomass of taxa. Species richness percentages for each phylum are calculated from the total pooled species richness across the 6 replicates.

Figure 5 Proportion of wet biomass (g m^{-2}) and species richness (N) of each phylum in the intersection 2 of Pelamis at ~0.50-2m water depth. Wet biomass percentages were calculated from the mean biomass of taxa of 3 replicates. Species richness is presented as the total number of different species recorded across the 3 replicates; barnacle/ serpulid shells were not included.

<<Editor: ''Species Richness'' should read ''Species richness''>>

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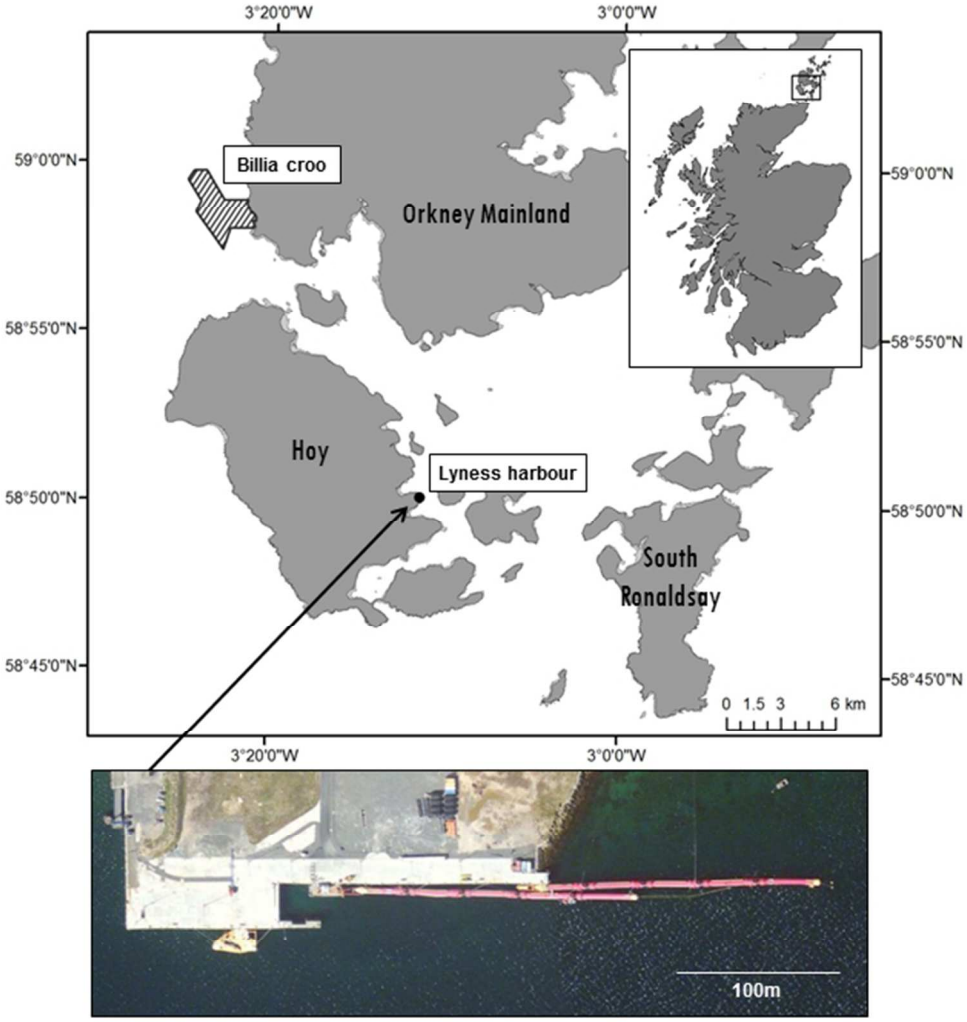
Figure 7 Proportional fouling composition on the two Pelamis devices, on the two sampling dates. Taxa included in each category listed in Table 2. Data are mean values of six photoquadrats.

Figure 8. 2-D MDS ordination of biofouling assemblages on Pelamis devices sampled in April 2014, using ROV photoquadrats. Hollow black triangles: P2-001, Solid grey triangles: P2-002. Numbers indicate the 'Can' for each photoquadrat.

Figure 9 Other areas on Pelamis that were not surveyed which were likely to provide differing environmental conditions for fouling organisms. a**.** the splash zone runs along the length of device; the image shows the presence of filamentous green algae. b. heat exchanger and the heat exchanger compartment fouled with hydroids; images courtesy of Rob Ionides. c./d. joints and crevices with aggregations of *M. edulis*; images courtesy of Angus Jackson.



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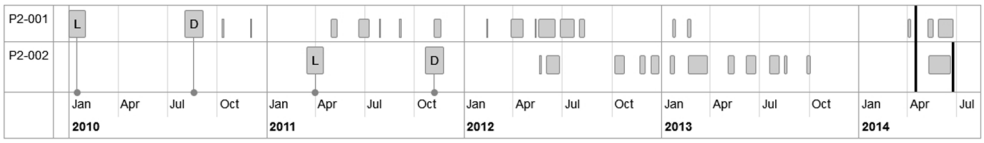

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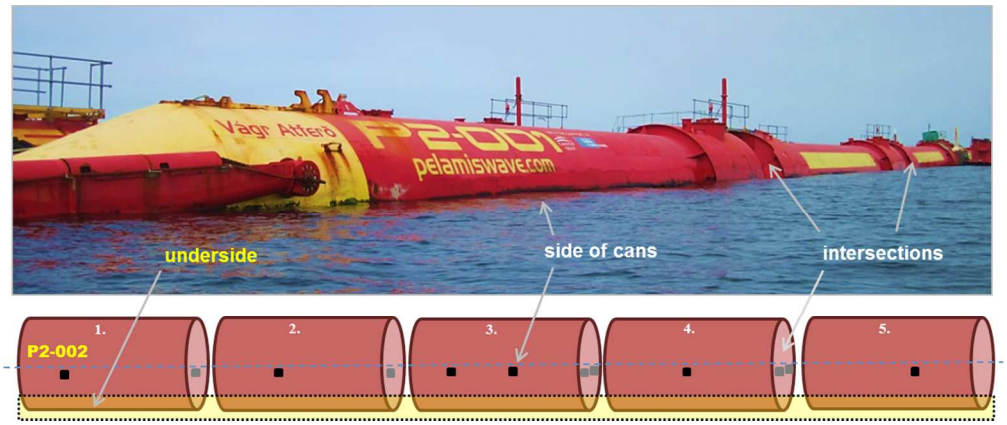

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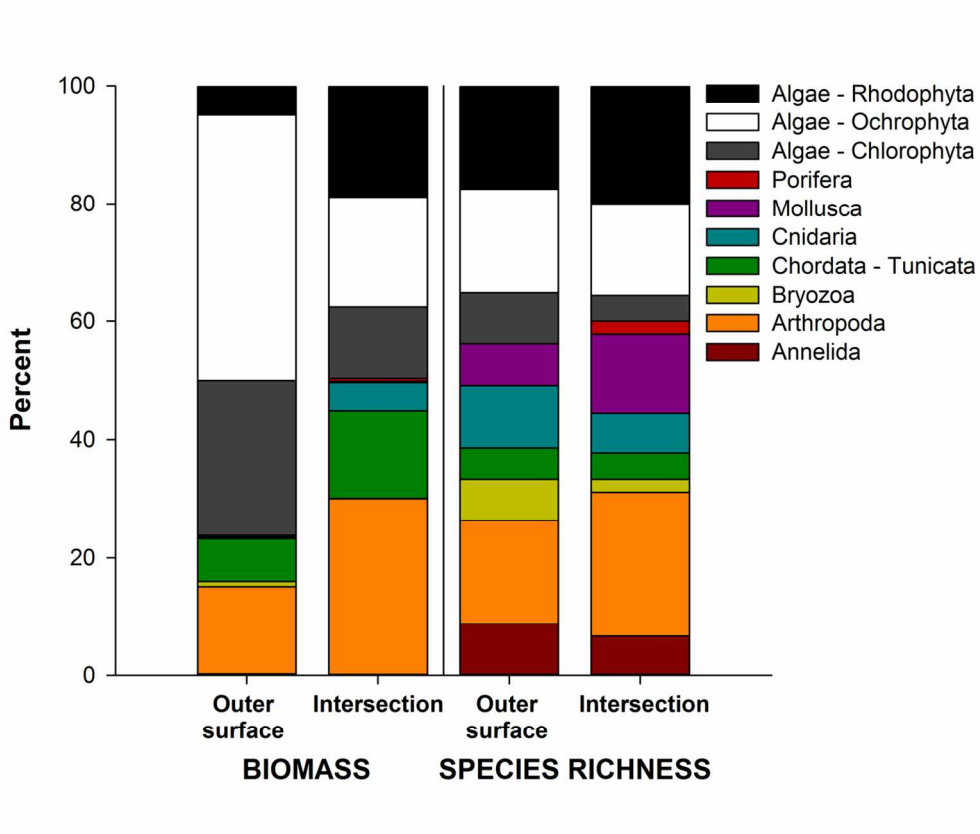
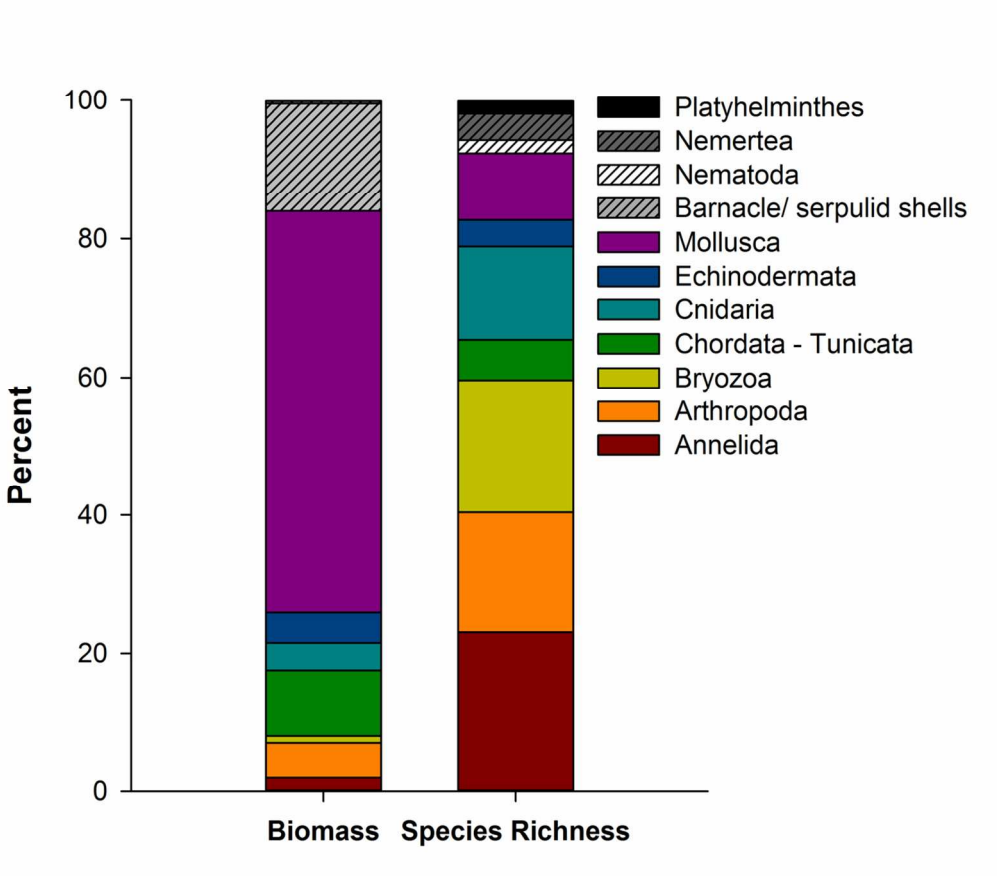


Figure 4 Proportion of wet biomass (g m-2) and species richness (N) of each phylum in the outer surface and intersection sample areas of P2-002 device at ~0-0.25m water depth. Wet biomass percentages were calculated from the mean biomass of taxa. Species richness percentages for each phylum are calculated from the total pooled species richness across the 6 replicates.

127x106mm (300 x 300 DPI)



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113x99mm (300 x 300 DPI)

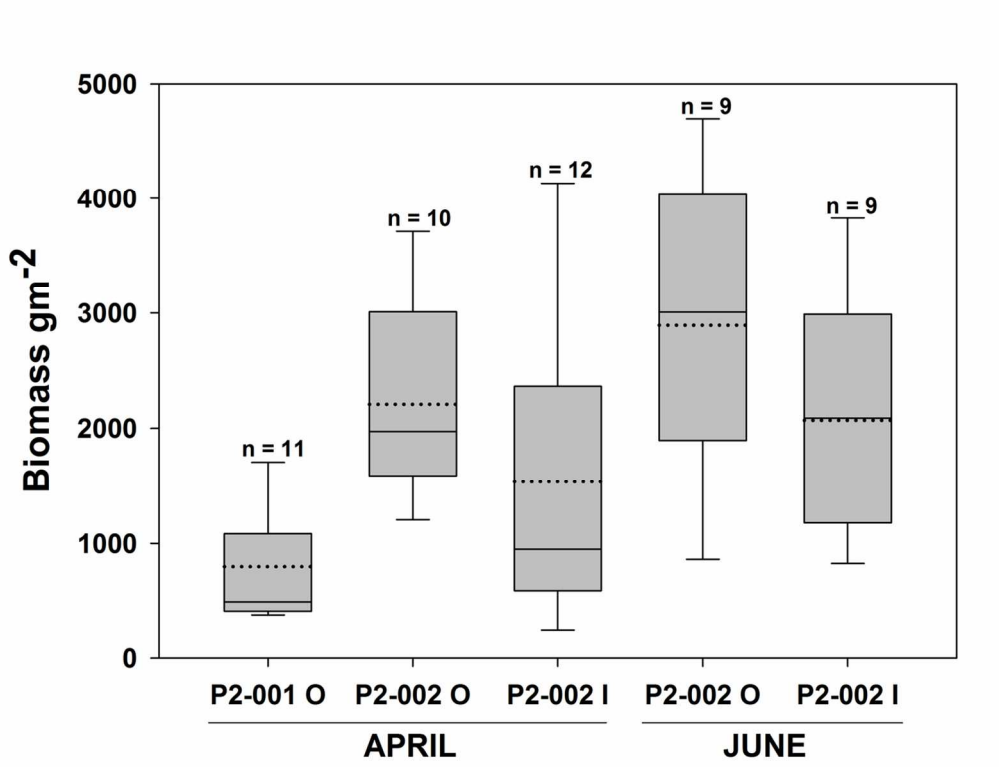

Figure 6 Wet biomass (g m-2) of samples collected from the outer surface of both devices in April 2014, and from both outer surface (O) and intersections (I) of the P2-002 device in April 2014 and June 2014. Dotted lines represent the mean value for each treatment.

120x92mm (300 x 300 DPI)

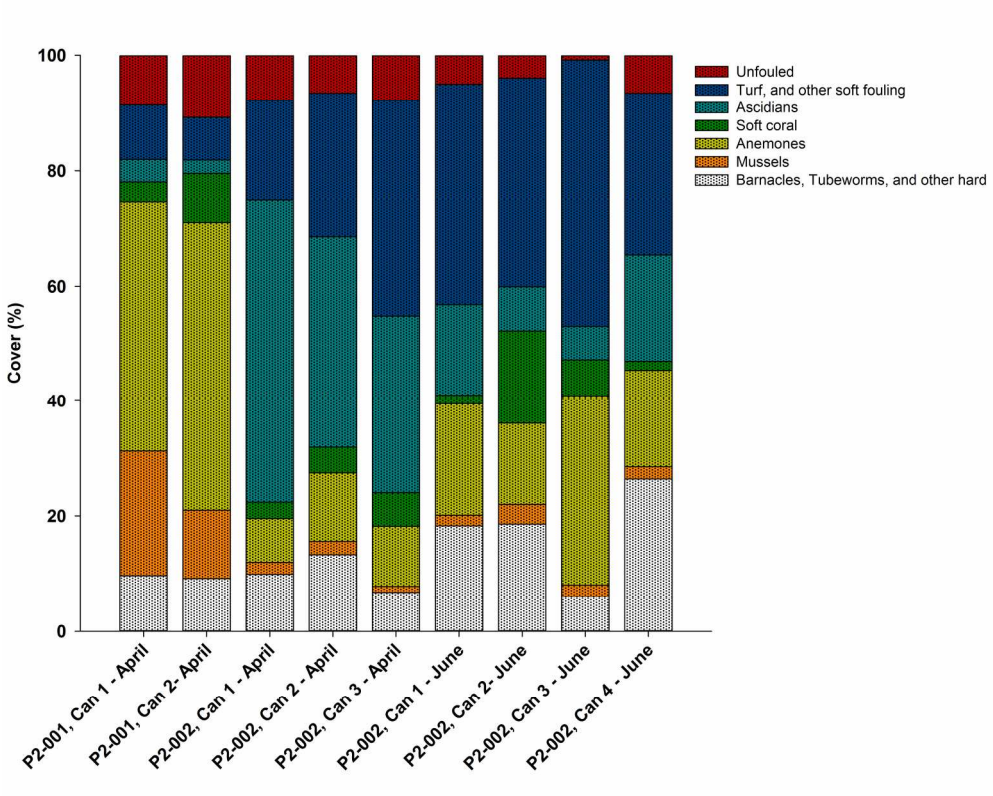

Figure 7 Proportional fouling composition on the two Pelamis devices, on the two sampling dates. Taxa included in each category listed in Table 2. Data are mean values of six photoquadrats.

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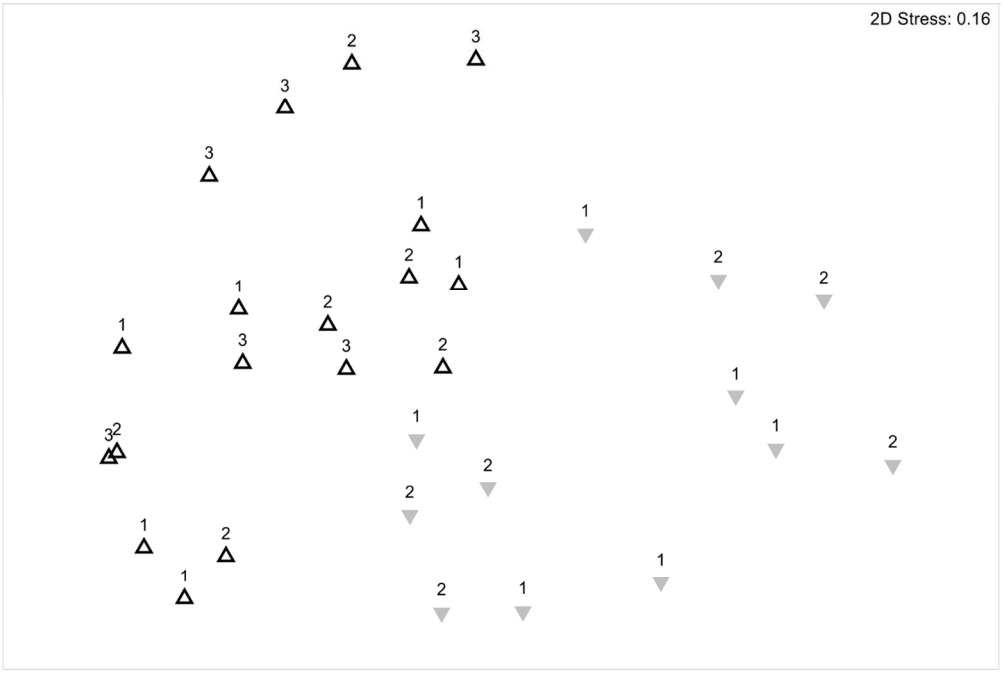


Figure 8 Two-dimensional nMDS ordination of biofouling assemblages on Pelamis devices sampled in April 2014, using ROV photoquadrats. Hollow black triangles: P2-001, Solid grey triangles: P2-002. Numbers indicate the 'Can' for each photoquadrat.

366x244mm (96 x 96 DPI)

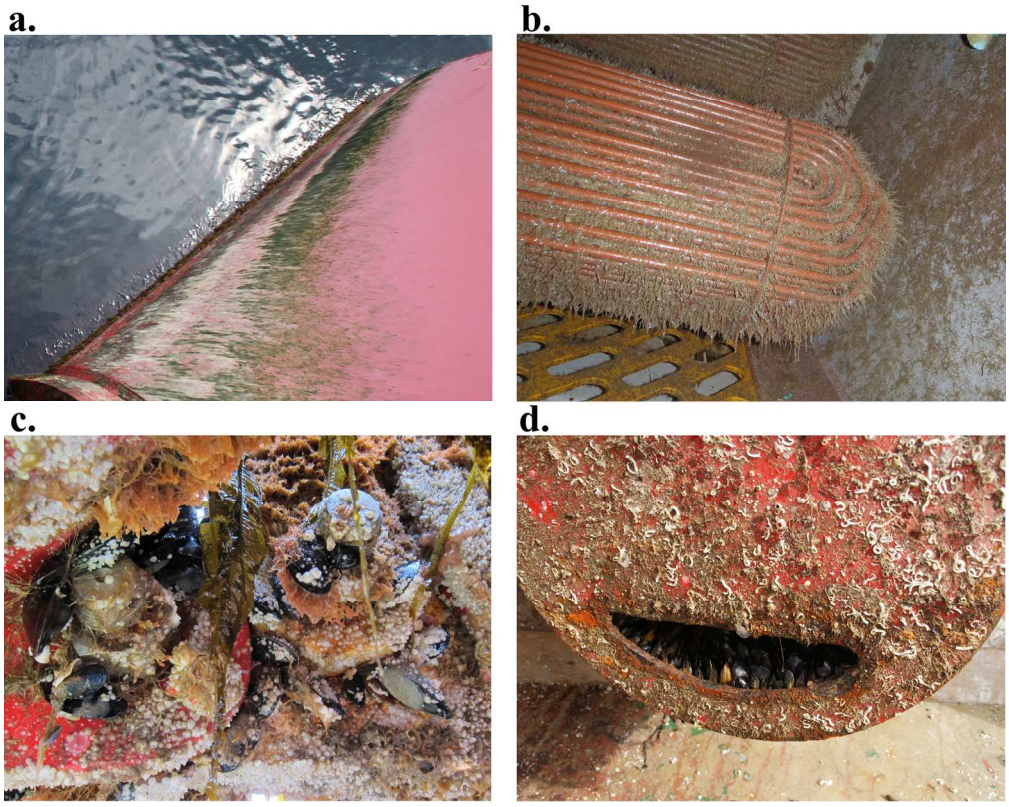


Figure 9 Other areas on Pelamis that were not surveyed which are likely to provide differing environmental conditions for fouling organisms. a. the splash zone runs along the length of device. The image shows the presence of filamentous green algae b. heat exchanger and the heat exchanger compartment fouled with hydroids. Images courtesy of Rob Ionides c./d. joints and crevices with aggregations of Mytilus edulis. Images courtesy of Angus Jackson.

705x564mm (72 x 72 DPI)

Table 1 Technical concerns for the wave energy industry associated with the accumulation of biofouling.

Operation	- Reduction in efficiency of energy extraction (Orme et al. 2001; Tiron et al. 2014) - Decreased buoyancy of floating structures (Anderson 2003) - Inhibition of moving parts such as release mechanisms (RenewableUK 2014) - Blockage to water intakes (Rajagopal & Jenner 2012; Blair et al. 2014) - Reduction in efficiency of heat exchangers (Terlizzi & Faimali 2010)
Longevity/ structural design	- Increased hydrodynamic loads and drag as a result of increased diameter and surface roughness will provide added strain on structures (Jusoh & Wolfram 1996; Yan & Yan 2003; Braithwaite & McEvoy 2005; Shi et al. 2012) - Reduction of structural natural frequencies (Fevåg 2012) - Increased structural weight (Anderson 2003; Shi et al. 2012)
Surface damage	- Accelerated corrosion caused by microorganisms (e.g. sulphate reducing bacteria) that thrive in the anaerobic microhabitats beneath biofouling (Beech et al. 2005) - Physical damage to coating when biofouling removed (Australian Government 2013)
Maintenance	- Increased drag leads to higher fuel consumption and time loss when towing devices (WHOI 1952; Schultz 2007) - Prevention of access to key areas during maintenance or monitoring, potentially concealing cracks or corrosion on the surface of the structure
Health and safety	- Deterioration of maintenance access equipment (e.g. ladders or components to attach lifting equipment) due to biofouling may make them too unsafe to use (RenewableUK 2014)

Table 2 Biofouling categories used for photoquadrat analysis.

Taxonomic group	Biofouling category
Algae	Algae (T)
Anthozoa	*Metridium dianthus* (An)
	Sagartia elegans (An)
	Urticina spp. (An)
	Unidentified anemone (An)
	Alcyonium digitatum (S)
Tunicata	Ascidiidae (As)
	Ciona intestinalis (As)
	Corella eumyota (As)
	Unidentified solitary ascidian (As)
	Botryllinae (As)
	Didemnidae eg *Diplosoma* sp. (As)
Porifera	*Sycon ciliatum* (T)
	Other sponges (T)
Bryozoa and hydrozoa	Encrusting bryozoans (T)
	Ectopleura or *Tubularia* spp. (T)
	Turf i.e. mixed hydroids, bryozoans and other small foulers, such as algae (T)
Crustacea	Barnacles (B)
Annelida	Tubeworms (B)
Mollusca	Mytilidae (M)
	Other bivalves (B)
	Gastropod egg mass (T)
Other	Calcareous remains eg barnacle and tubeworm casts (B)
	Unidentified hard biofouling (B)
	Unidentified soft biofouling (T)
	Unidentifiable biofouling (T)
	Unfouled visible painted surface (U)

Broader categories used in Figure 7 are shown in parenthesis: T = turf, other soft fouling; An = anemones; S = soft coral; As = ascidians; B = barnacles, tubeworms, other hard fouling; M = mussels; U = unfouled.

Table 3 Contribution of taxa to the average Bray-Curtis dissimilarity (δ) of biofouling assemblages between depth categories (~0-0.25m, ~0.50-2m) in the intersections (SIMPER analysis).

~0-0.25m *vs* ~0.5-2m δ = 82.55					
Taxa	0-0.25m Average abundance ($\sqrt[4]{g\ m^{-2}}$)	0.5-2m Average abundance ($\sqrt[4]{g\ m^{-2}}$)	$\overline{\delta_i}$	$\overline{\delta_i}$/SD	Contribution %
Empty barnacles/ serpulid cases	0	5.4	5.57	3.91	6.75
Alaria esculenta	3.66	0	3.84	2.16	4.65
Ascidiella aspersa	0.29	3.75	3.62	2.62	4.38
Ulva sp.	3.34	0	3.57	1.82	4.32
Mytilus edulis	0.2	4.1	3.3	1.04	3.99
Polysiphonia sp.	2.9	0	2.77	1.94	3.36
Metridium dianthus	0	2.43	2.3	3.29	2.79
Eudendrium sp.	0	2.37	2.28	4.33	2.77
Hiatella arctica	0.34	2.52	2.27	2.11	2.75
Diplosoma listerianum	2.68	4.14	2.24	1.15	2.71
Balanus crenatus	3.53	3.28	2.1	1.55	2.55
Nereis pelagica	0.14	2.14	2.07	3.25	2.51
Spirobranchus triqueter	0.26	2.25	1.99	2.15	2.41
Anomia ephippium	0.77	1.98	1.91	1.51	2.31
Balanus balanus	0	1.6	1.77	1.24	2.15

The average dissimilarity of each taxon (δi) represents the contribution of the taxa to dissimilarity. The ratio of contribution (δi /SD) represents the consistency of this contribution across replicates. Taxa are ordered by their % contribution to the δ. Only species contributing the most to dissimilarity are displayed (species contributing >50% to the δ).

Table 4 Two-way nested PERMANOVA comparing assemblage composition on the underside of the two PELAMIS devices in April 2014, based on photoquadrat data.

	df	SS	MS	Pseudo-F	*p*	Permutations
Device	1	12608	12608	11.612	**0.001**	999
Can (device)	3	2576.8	858.94	0.791	0.667	995
Residual	25	27145	1085.8			
Total	29	42330				

Table 5 Contribution of fouling categories to Bray-Curtis dissimilarity (δ) of fouling assemblages between the two Pelamis devices (SIMPER analysis), surveyed in April 2014.

Fouling category	P2-001 Mean abundance	P2-002 Mean abundance	$\overline{\delta_i}$	$\overline{\delta_i}$/SD	Contribution %
Metridium dianthus	2.28	0.64	7.36	1.53	12.44
Didemnidae	0.50	2.24	7.31	1.69	12.36
Mytilidae	1.69	0.55	5.24	1.5	8.86
Turf	0.95	2.00	4.82	0.32	8.14
Urticina spp.	0.28	1.13	4.02	0.26	6.79
Alcyonium digitatum	1.07	0.90	3.55	1.18	5.99

Categories are listed in descending order of contribution to δ, only species contributing >50% are displayed. Abundances are fourth-root transformed percent cover data, averaged across all cans for each device.

Table 6 Two-way nested PERMANOVA comparing assemblage composition on the underside of P2-002 sampled in April and June 2014, based on photoquadrat data.

	df	SS	MS	Pseudo-F	*p*	Permutations
Sampling date	1	3792.2	3792.2	4.1219	**0.001**	999
Can (Sampling date)	5	8551.3	1710.3	1.8589	**0.005**	998
Residuals	35	32201	920.01			
Total	41	44544				
Pairwise tests	Within April			Within June		
	t	*p*	Permutations	t	*p*	Permutations
Can 1 *vs* Can 2	0.933	0.476	407	1.441	**0.03**	413
Can 1 *vs* Can 3	1.422	0.101	415	1.897	**0.003**	404
Can 1 *vs* Can 4	n/a	n/a	n/a	1.164	0.292	401
Can 2 *vs* Can 3	1.056	0.344	409	1.555	**0.034**	407
Can 2 *vs* Can 4	n/a	n/a	n/a	1.231	0.168	417
Can 3 *vs* Can 4	n/a	n/a	n/a	1.594	**0.016**	409

Results of pairwise comparisons are included between all levels of factor 'Can' within both levels of factor 'Sampling date'.

Table 7 Contribution of fouling categories to Bray-Curtis dissimilarity (δ) of fouling assemblages between P2-002 surveyed in April and June 2014 (SIMPER analysis).

Fouling category	April Mean abundance	June Mean abundance	$\overline{\delta_i}$	$\overline{\delta_i}$/SD	Contribution %
Didemnidae	2.24	1.23	4.54	1.27	9.75
Urticina spp.	1.13	1.59	3.61	1.07	7.77
Barnacles	1.00	1.62	3.32	1.15	7.14
Alcyonium digitatum	0.90	1.02	3.31	1.13	7.11
Metridium dianthus	0.64	0.78	3.03	1.05	6.52
Tubeworms	0.58	0.96	2.94	1.18	6.31
Ascidiidae	0.71	0.79	2.73	1.14	5.87

Categories are listed in descending order of contribution to δ, only species contributing >50% are displayed. Abundances are fourth-root transformed percentage cover data, averaged across all cans for each sampling date.

Characterisation of the biofouling community on a floating wave energy device

Christopher R. Nall, Marie-Lise Schläppy, Andrew J. Guerin

Supplementary material

a.

b.

c.

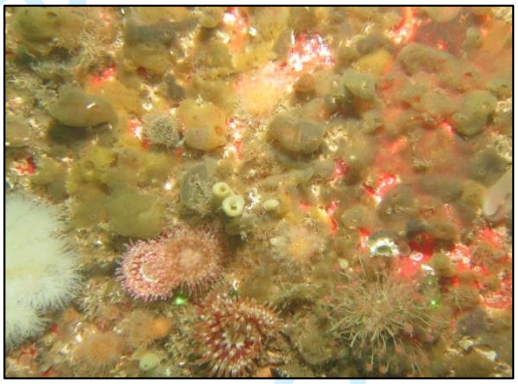


Figure S1 Images of the biofouling from sampling areas of the Pelamis wave energy convertor. **a.** front section of P2-001 device which had been removed from water for maintenance; this algal community is similar in appearance to biofouling sampled from the waterline of the P2-002 device. Image courtesy of Angus Jackson. **b**. intersection of P2-002 device at ~0.5-2m water depth; image courtesy of Rob Ionides **c.** underside of P2-002 device; image taken using the ROV stills camera.

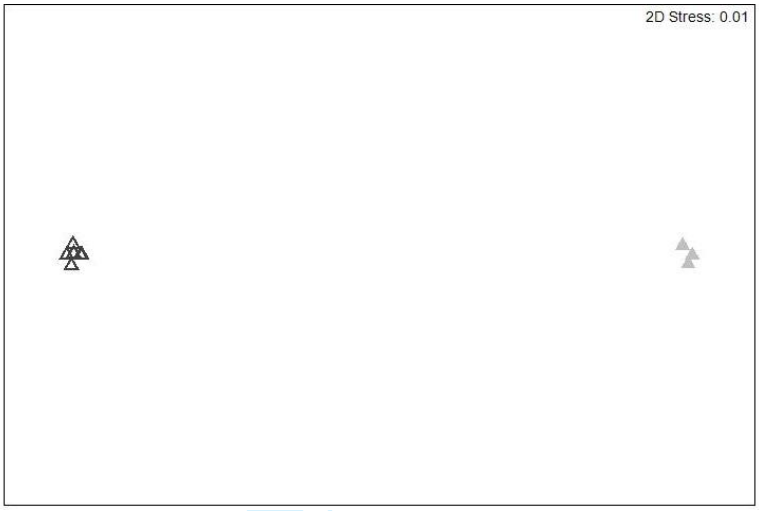
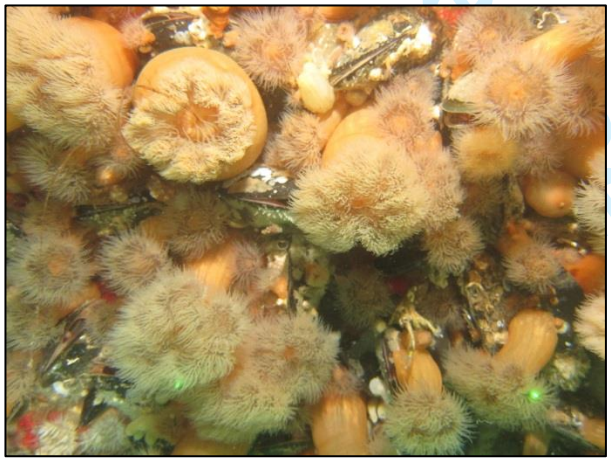
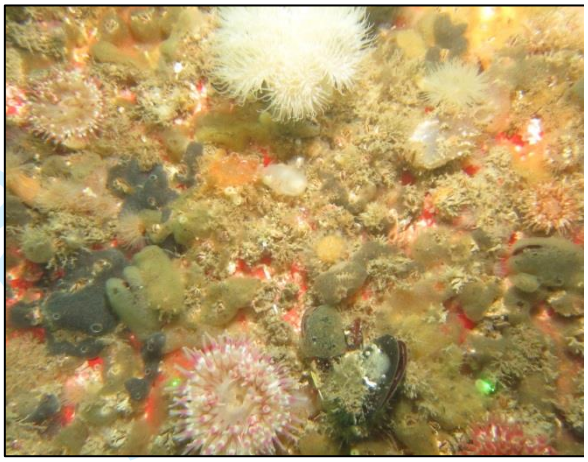


Figure S2 MDS ordination of biofouling assemblages from just below the waterline (~0-0.25m) and at ~0.5-2m depth in the intersections of Pelamis. Solid grey triangles = ~0.5-2m; Black hollowed triangles = ~0-0.25m. A stress value of <0.2 indicates the MDS plot accurately represents the similarity rankings (Clarke and Warwick 2001)

P2-001 April 2014



P2-002 April 2014



P2-002 June 2014

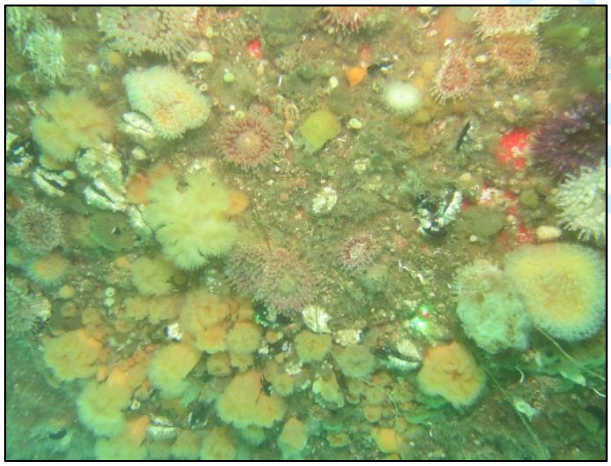


Figure S3 Photoquadrats representing biofouling communities on the underside of P2-001 and P2-002 devices in April 2014 and P2-002 in June 2014.

Table S1 Image quality scoring scheme

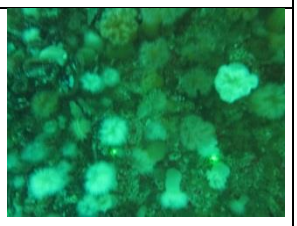
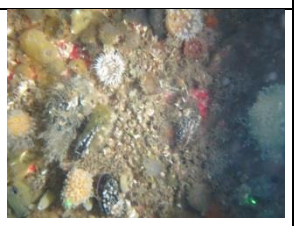
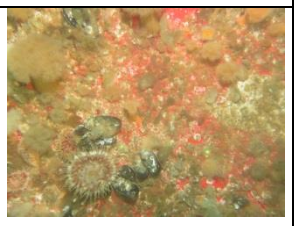
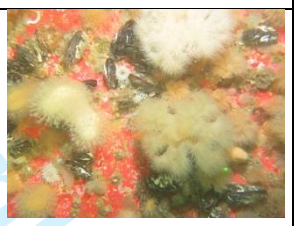
Image Quality Score	Criteria	Example images
0 – 'Junk'	• Image shows no species or features of interest • Image too blurry / out of focus for reliable species identification	
1 – 'Poor'	• Image badly lit • Image out of focus • Image taken from too far away for species ID • Image poorly aligned with features • Some general species ID may be possible	
2 – 'OK'	• Better focus and/or illumination • Some species ID possible, but not quantitative • Image may not be well aligned with device features	
3 – 'Good'	• Generally good focus and mostly even illumination • Biofouling ID consistently possible • Image well aligned – facing flat surface (device underside) directly • Both laser scaling points visible • Field of view not too large (no more than approximately 2-3 times the distance between the laser scaling points)	
4 – 'Excellent'	• Good focus and even illumination • Biofouling ID consistently possible • Image well aligned • Both laser scaling points visible • Field of view of similar magnitude to the distance between the two laser scaling points	

Table S2 Species inventory for biofouling community on the Pelamis wave energy devices. Mean wet biomass (g m^{-2} ±s.e.) is given for destructive scrape sampling where available. *species only recorded on P2-001 in 'Opportunistic' images (not used in photoquadrat analyses), †species only recorded on P2-002 in ROV images captured in June 2014. Non-native species and cryptogenic species are underlined.

Phyla	Species (or highest taxonomic resolution)	Destructive scrape sampling of P2-002 (mean biomass, g m^{-2} ± standard error)			ROV images of underside	
		Shallow (0 – 0.25 m depth)		Deep Intersection (0.5 – 2m depth)		
		Outer surface	Intersection		P2-001	P2-002
Annelida	Aphroditoidea					Present
	Amblyosyllis formosa			0.3 ± 0.15		
	Arenicolides ecaudata			0.89 ± 0.89		
	Eumida sanguinea			0.01 ± 0.01		
	Eupolymnia nebulosa			1.2 ± 1.18		
	Hydroides norvegicus			7.41 ± 4.51	Present	Present
	Nereimyra puncata			1.13 ± 0.39		
	Nereis pelagica	1.7 ± 1.29	0.07 ± 0.07	22.96 ± 7.03		
	Phyllodoce sp.	2.37 ± 2.11		3.7 ± 3.7		
	Polynoinae spp.	0.52 ± 0.52		9.63 ± 5.42		
	Sabella pavonina			23.85 ± 23.85	Present *	Present †
	Serpula vermicularis				Present	Present
	Spirobranchus triqueter	0.67 ± 0.67	0.23 ± 0.22	43.27 ± 23.88	Present	Present
	Syllis sp.	0.38 ± 0.21	0.22 ± 0.1	1.93 ± 1.04		
Arthropoda - Chelicerata	*Phoxichilidium femoratum*	0.15 ± 0.15	0.59 ± 0.42			
	Pycnogonida (unidentified)					Present
Arthropoda - Crustacea	*Ampithoe gammaroides*	0.22 ± 0.22				
	Balanus balanus			37.78 ± 34.71	Present	Present †
	Balanus crenatus	323.71 ± 187.46	528.37 ± 286.62	195.11 ± 148.07	Present	Present
	Cancer pagurus			1.63 ± 1.63		

Phyla	Species (or highest taxonomic resolution)	Destructive scrape sampling of P2-002 (mean biomass, g m^{-2} ± standard error)			ROV images of underside	
		Shallow (0 – 0.25 m depth)		Deep Intersection (0.5 – 2m depth)		
		Outer surface	Intersection		P2-001	P2-002
Arthropoda - Crustacea	*Caprella mutica*			2.96 ± 1.67	Present *	
	Chirona hameri				Present	Present
	Dexamine thea	0.08 ± 0.07	0.07 ± 0.07			
	Gammarellus angulosus	31.04 ± 22.36	2.52 ± 1.24	0.44 ± 0.44		
	Galathea sp.				Present *	
	Hyale pontica		0.15 ± 0.15			
	Hyas sp.			6.84 ± 4.45	Present *	
	Idotea granulosa		3.98 ± 2.11			
	Idotea pelagica	3.33 ± 1.1	4.59 ± 3.1			
	Jassa herdmani	0.45 ± 0.3	0.82 ± 0.81	0.3 ± 0.15		
	Juvenile crab			1.48 ± 0.74		
	Monocorophium sp.	0.01 ± 0.01	0.09 ± 0.07			
	Necora puber			23.41 ± 23.41		
	Munna sp.		0.07 ± 0.07			
	Verruca stroemia	0.07 ± 0.07				
Arthropoda - Hexapoda	Chironomidae Larva	0.01 ± 0.01	0.08 ± 0.07			
Bryozoa	*Bugulina fulva*			Present		
	Callopora dumerilii			10.96 ± 10.96		
	Celleporella hyalina	0.23 ± 0.15	0.23 ± 0.15	15.41 ± 11.26		
	Celleporina caliciformis			6.83 ± 6.83		
	Cyclostomatida			0.3 ± 0.3		
	Electra pilosa	13.93 ± 13.66		0.3 ± 0.3	Present *	
	Membranipora membranacea	6.89 ± 6.89				

Phyla	Species (or highest taxonomic resolution)	Destructive scrape sampling of P2-002 (mean biomass, g m^{-2} ± standard error)			ROV images of underside	
		Shallow (0 – 0.25 m depth)		Deep Intersection (0.5 – 2m depth)		
		Outer surface	Intersection		P2-001	P2-002
Bryozoa	*Microporella ciliata*			0.03 ± 0.01		
	Schizoporella japonica	0.15 ± 0.15		Present	Present *	
	Scrupocellaria scruposa			32.31 ± 32.29		
	Tubulipora sp.			0.59 ± 0.59		
Chordata - Osteichthyes	*Taurulus* sp.				Present	
Chordata - Tunicata	*Ascidiella aspersa*	9.26 ± 9.26	1.56 ± 1.56	220.44 ± 87.99	Present	Present
	Ascidiella scabra					Present
	Botrylloides spp.					Present
	Botryllus schlosseri				Present	Present
	Ciona intestinalis				Present	Present
	Corella eumyota			0.59 ± 0.59	Present *	Present
	Diplosoma listerianum	166.15 ± 64.7	265.7 ± 168.05	300.96 ± 52.86	Present	Present
	Molgula sp.	0.15 ± 0.15				
Cnidaria - Anthozoa	*Alcyonium digitatum*			17.3 ± 17.3	Present	Present
	Metridium dianthus	0.89 ± 0.89		86.96 ± 78.34	Present	Present
	Sagartia elegans var. miniata				Present	Present
	Sagartia elegans var. nivea				Present	Present
	Sagartia elegans var. venusta				Present	Present
	Urticina eques				Present	Present
	Urticina felina				Present	Present
Cnidaria - Hydrozoa	*Bougainvillia muscus*	0.44 ± 0.36				
	Clytia hemisphaerica	0.37 ± 0.37	21.41 ± 13.59	9.24 ± 9.24		

Phyla	Species (or highest taxonomic resolution)	Destructive scrape sampling of P2-002 (mean biomass, g m^{-2} ± standard error)			ROV images of underside	
		Shallow (0 – 0.25 m depth)		Deep Intersection (0.5 – 2m depth)		
		Outer surface	Intersection		P2-001	P2-002
Cnidaria - Hydrozoa	*Coryne eximia*	0.96 ± 0.8				
	Eudendrium sp.			57.19 ± 41.81		
	Halecium sp.			0.01 ± 0.01		
	Obelia sp.	0.01 ± 0.01	0.3 ± 0.29	1.81 ± 1.81		
	Tubularia sp.	0.15 ± 0.15	63.63 ± 57.3	33.85 ± 23.24	Present	Present
Echinodermata	*Asterias rubens*			240.74 ± 240.74	Present *	
	Echinus esculentus			Present	Present	Present
	Ophiothrix fragilis				Present *	Present †
Mollusca - Bivalvia	*Anomia ephippium*	1.19 ± 0.82	1.41 ± 0.64	53.04 ± 29.03	Present	Present
	Hiatella arctica	0.74 ± 0.74	0.37 ± 0.24	60.15 ± 36.55		
	Mytilus edulis	2.37 ± 2.28	0.37 ± 0.37	3072.74 ± 3070.3	Present	Present
Mollusca - Gastropoda	*Aeolidia papillosa*				Present	Present
	Doto sp.		0.15 ± 0.15	0.01 ± 0.01		
	Flabellina sp.	0.01 ± 0.01	0.81 ± 0.54			
	Patella vulgata				Present *	
	Rissoa sp.		0.75 ± 0.58	0.3 ± 0.3		
Nematoda	Nematode sp.			0.01 ± 0.01		
Nemertea	*Nemertea* cf. *Emplectonema neesii*			16.74 ± 16.74		
	Nemertea sp.			8.74 ± 8.74		
Porifera	*Leucosolenia* sp.		8.15 ± 8.15			
	Sycon ciliatum				Present	Present
Platyhelminthes	*Stylostomum ellipse*			1.63 ± 0.97		

Phyla	Species (or highest taxonomic resolution)	Destructive scrape sampling of P2-002 (mean biomass, g m^{-2} ± standard error)			ROV images of underside	
		Shallow (0 – 0.25 m depth)		Deep Intersection (0.5 – 2m depth)		
		Outer surface	Intersection		P2-001	P2-002
Misc.	Empty barnacle/ serpulid shells	6.74 ± 5.59		853.78 ± 71.5		
	Egg mass		0.22 ± 0.22			
ALGAE						
Chlorophyta	*Acrosiphonia arcta*	321.19 ± 110.26	2.15 ± 0.99			
	Cladophora sp.	2.67 ± 2.67				
	Filamentous green spp.	11.93 ± 7.48				
	Ulva sp.	295.11 ± 119.01	217.93 ± 99.04		Present	
Ochrophyta - Phaeophyceae	*Alaria esculenta*	415.04 ± 150.3	296.46 ± 117.83		Present *	
	Ascophyllum nodosum				Present *	
	Chorda filum	199.56 ± 62.54	3.93 ± 2.68			Present †
	Desmarestia aculeata	9.11 ± 6.8				
	Desmarestia viridis	36.39 ± 35.66	1.49 ± 1.23			
	Filamentous brown spp. (mixture of *Ectocarpus* and *Hincksia* species)	112.52 ± 38.23	23.93 ± 15.73			
	Kelp holdfast	27.56 ± 27.56				
	Laminaria spp.	56.59 ± 28.14	6.52 ± 2.9		Present *	
	Petalonia fascia	6.96 ± 4.61	1.19 ± 1.19			
	Saccharina latissima	203.85 ± 203.85				
	Scytosiphon lomentaria	26 ± 26	3.7 ± 3.7			
	Thin branched brown sp.	2.44 ± 2.44				
Rhodophyta	*Aglaothamnion* sp.	0 ± 0	19.41 ± 17.2			
	Ceramium sp.	4.53 ± 2.69	33.93 ± 21.18			
	Dasysiphonia japonica	37.19 ± 29.49	17.93 ± 12.41			
	Lomentaria clavellosa	0.3 ± 0.3	5.63 ± 3.65			

Phyla	Species (or highest taxonomic resolution)	Destructive scrape sampling of P2-002 (mean biomass, g m^{-2} ± standard error)			ROV images of underside	
		Shallow (0 – 0.25 m depth)		Deep Intersection (0.5 – 2m depth)		
		Outer surface	Intersection		P2-001	P2-002
Rhodophyta	*Lomentaria orcadensis*	1.7 ± 1.7	0.22 ± 0.22			
	Filamentous red spp.	11.04 ± 9.22	4.21 ± 4.21			
	Palmaria palmata	0.37 ± 0.37				
	Polysiphonia sp.	57.41 ± 37.52	257.93 ± 155.59			
	Porphyra sp.	0.67 ± 0.67			Present *	
	Pterothamnion plumula	0.01 ± 0.01				
	Red encrusting				Present *	Present †
Bacillariophyta	*Licmophora* sp.		0.37 ± 0.37			

Table S3 GLM analysis, comparing biomass between sub-habitat and deployment factors on the P2-002 device. Deployment factor refers to the treatment levels: pre- and post-deployment at the energy extraction site

Source	**df**	**MS**	**F**	***p***
Sampling area	1	19.595	5.220	**0.028**
Deployment	1	11.800	3.144	0.085
Sampling area*Deployment	1	0.273	0.073	0.789
Residual	36	3.754		

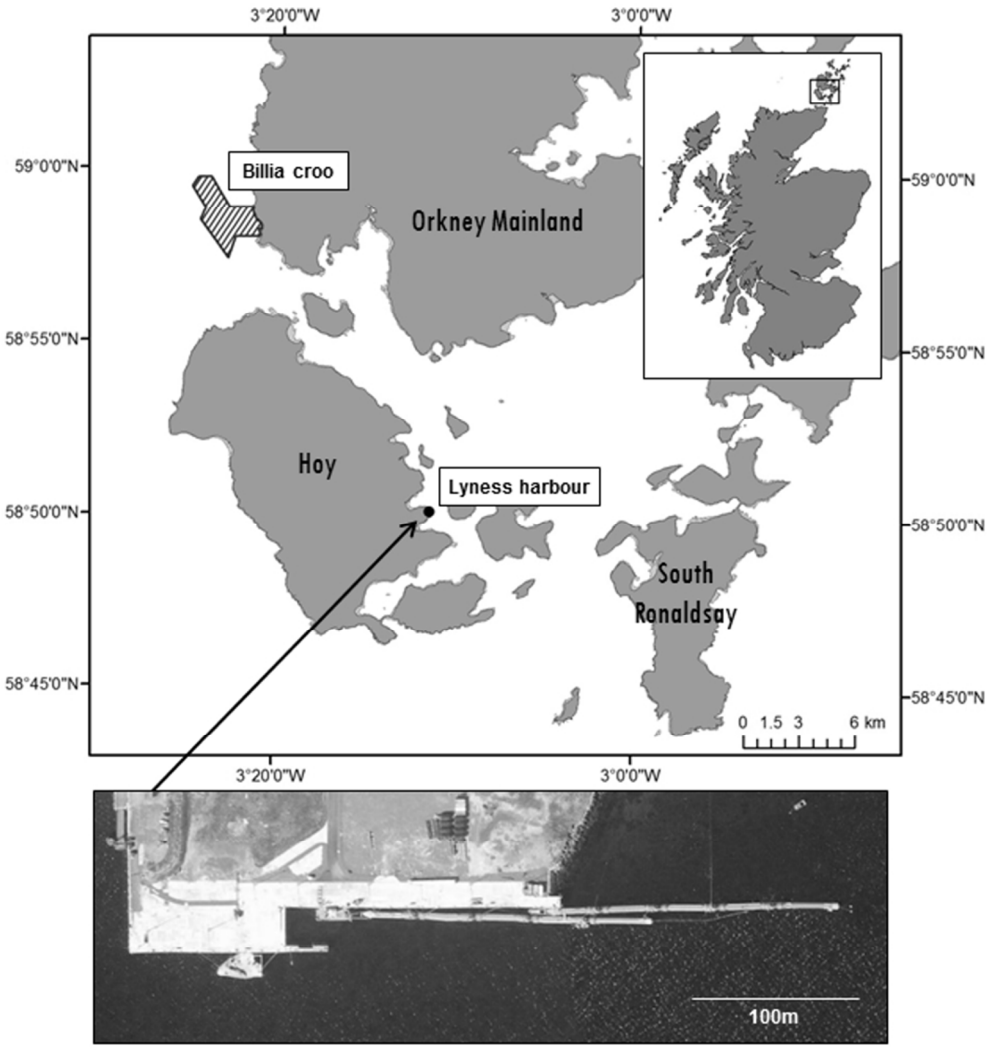


Figure 1 Locations for the Billia Croo wave test site and Lyness harbour renewable energy storage and maintenance facility in the Orkney Islands, Scotland. The aerial image of Lyness Harbour shows the P2-001 and P2-002 Pelamis wave energy converters berthed alongside the wharf. Image source for Lyness aerial image: http://www.bing.com/maps/

252x266mm (96 x 96 DPI)

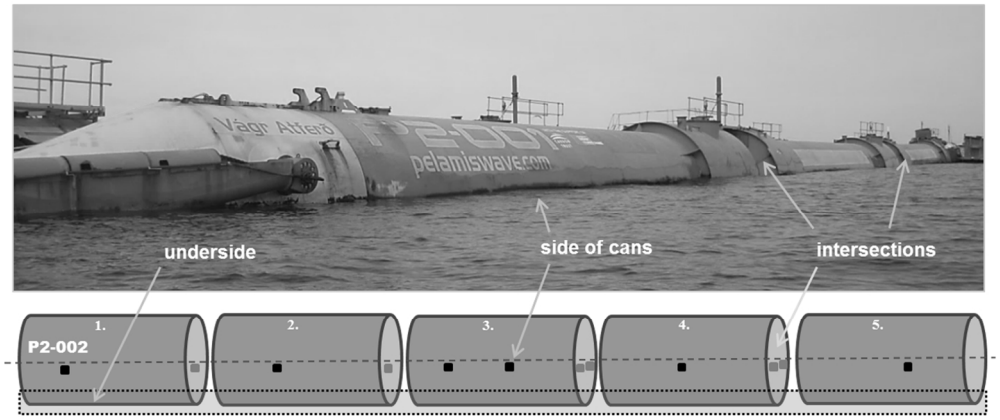


Figure 3 Biofouling sampling plan for the Pelamis wave energy converter. Replicates from the outer surface are displayed in black and replicates from the intersections are displayed in grey (n=12). Some cans were sampled twice to maintain a balanced experimental design. Deeper sampling (~0.5m-2m depth) was also carried out at intersection 2 and 3.

365x155mm (96 x 96 DPI)

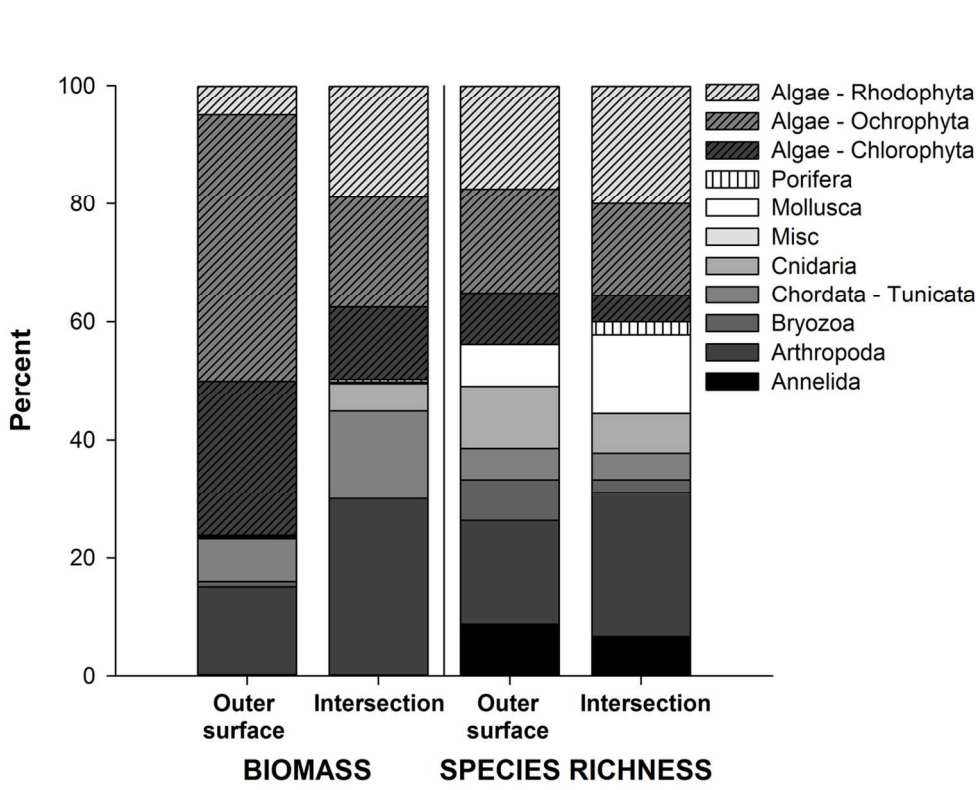


Figure 4 Proportion of wet biomass (g m-2) and species richness (N) of each phylum in the outer surface and intersection sample areas of P2-002 device at ~0-0.25m water depth. Wet biomass percentages were calculated from the mean biomass of taxa. Species richness percentages for each phylum are calculated from the total pooled species richness across the 6 replicates.

120x95mm (300 x 300 DPI)

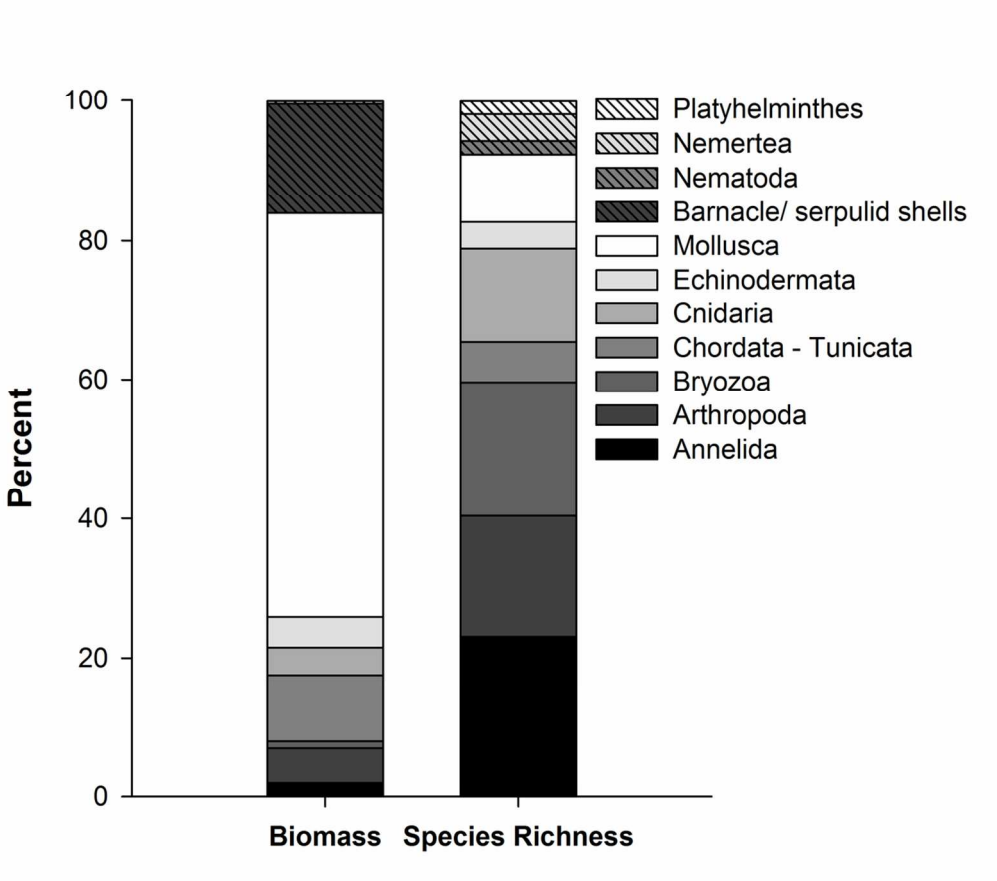


Figure 5 Proportion of wet biomass (g m-2) and species richness (N) of each phylum in the intersection 2 of Pelamis at ~0.50-2m water depth. Wet biomass percentages were calculated from the mean biomass of taxa of 3 replicates. Species richness is presented as the total number of different species recorded across the 3 replicates; barnacle/ serpulid shells were not included.

113x100mm (300 x 300 DPI)

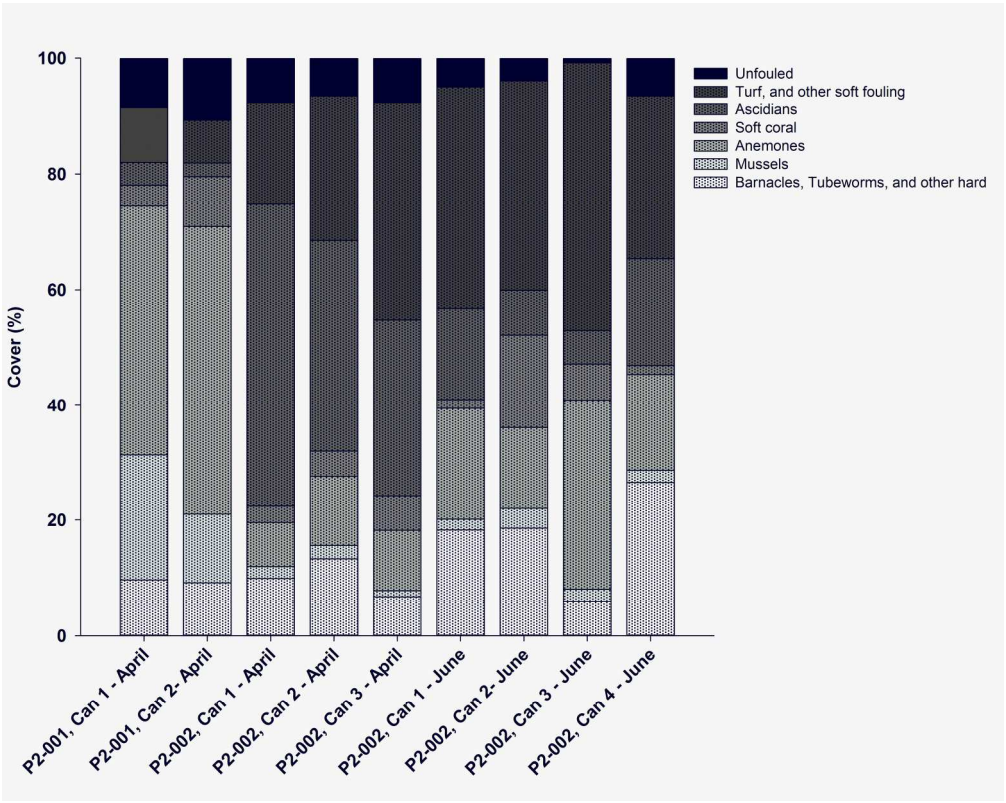


Figure 7 Proportional fouling composition on the two Pelamis devices, on the two sampling dates. Taxa included in each category listed in Table 2. Data are mean values of six photoquadrats.

193x154mm (300 x 300 DPI)

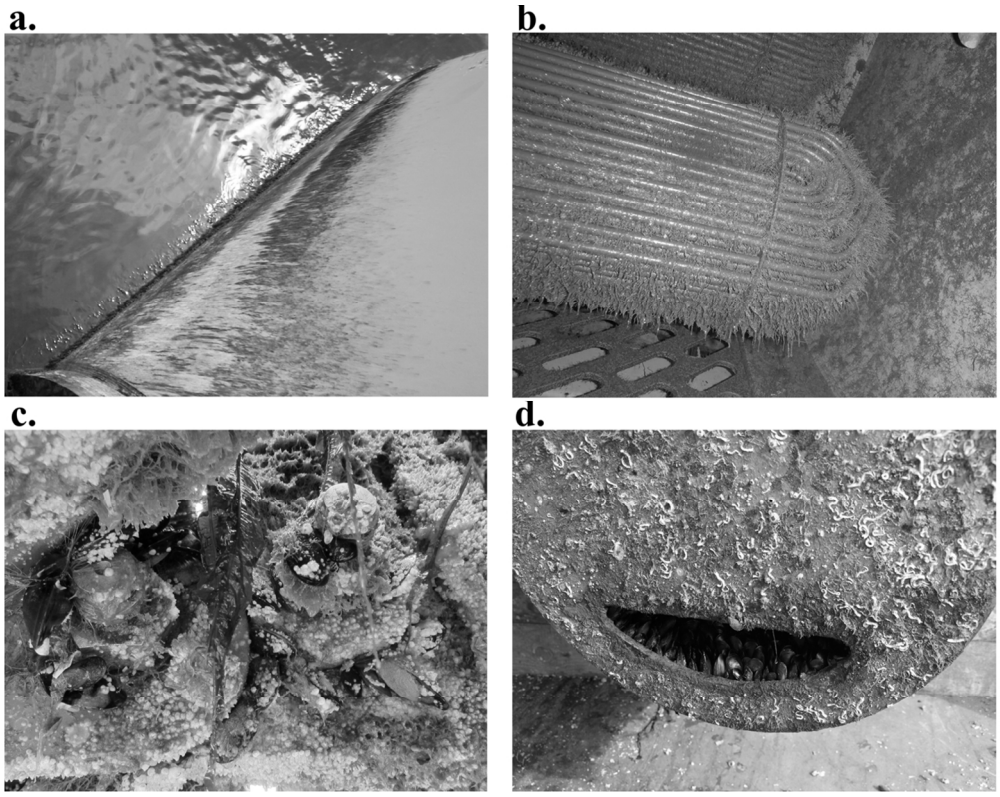


Figure 9 Other areas on Pelamis that were not surveyed which are likely to provide differing environmental conditions for fouling organisms. a. the splash zone runs along the length of device. The image shows the presence of filamentous green algae b. heat exchanger and the heat exchanger compartment fouled with hydroids. Images courtesy of Rob Ionides c./d. joints and crevices with aggregations of Mytilus edulis. Images courtesy of Angus Jackson.

360x285mm (96 x 96 DPI)